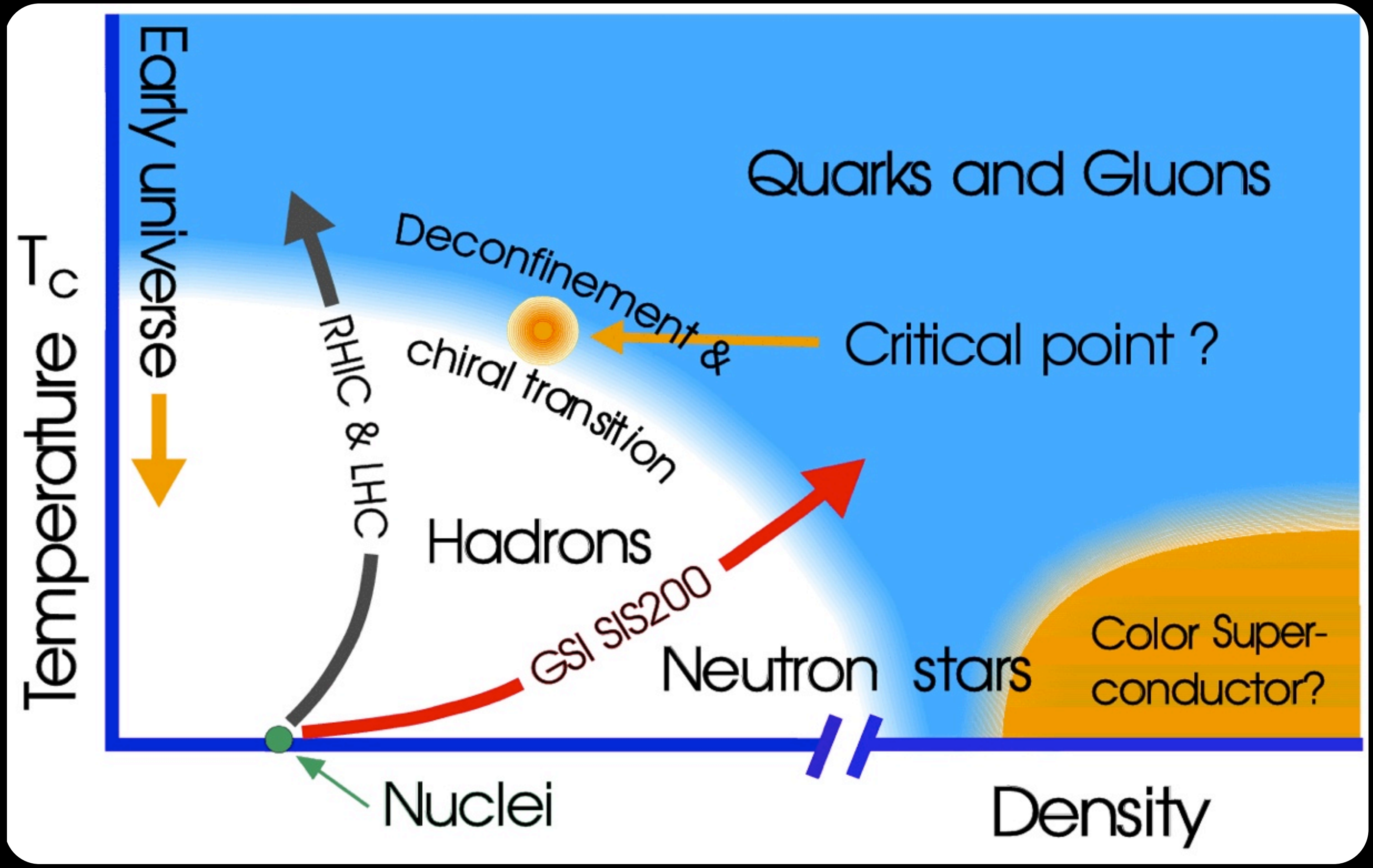
Anisotropic Flow at RHIC and at the LHC

ICFP Kolymbari, Crete 2012

Raimond Snellings
Utrecht University

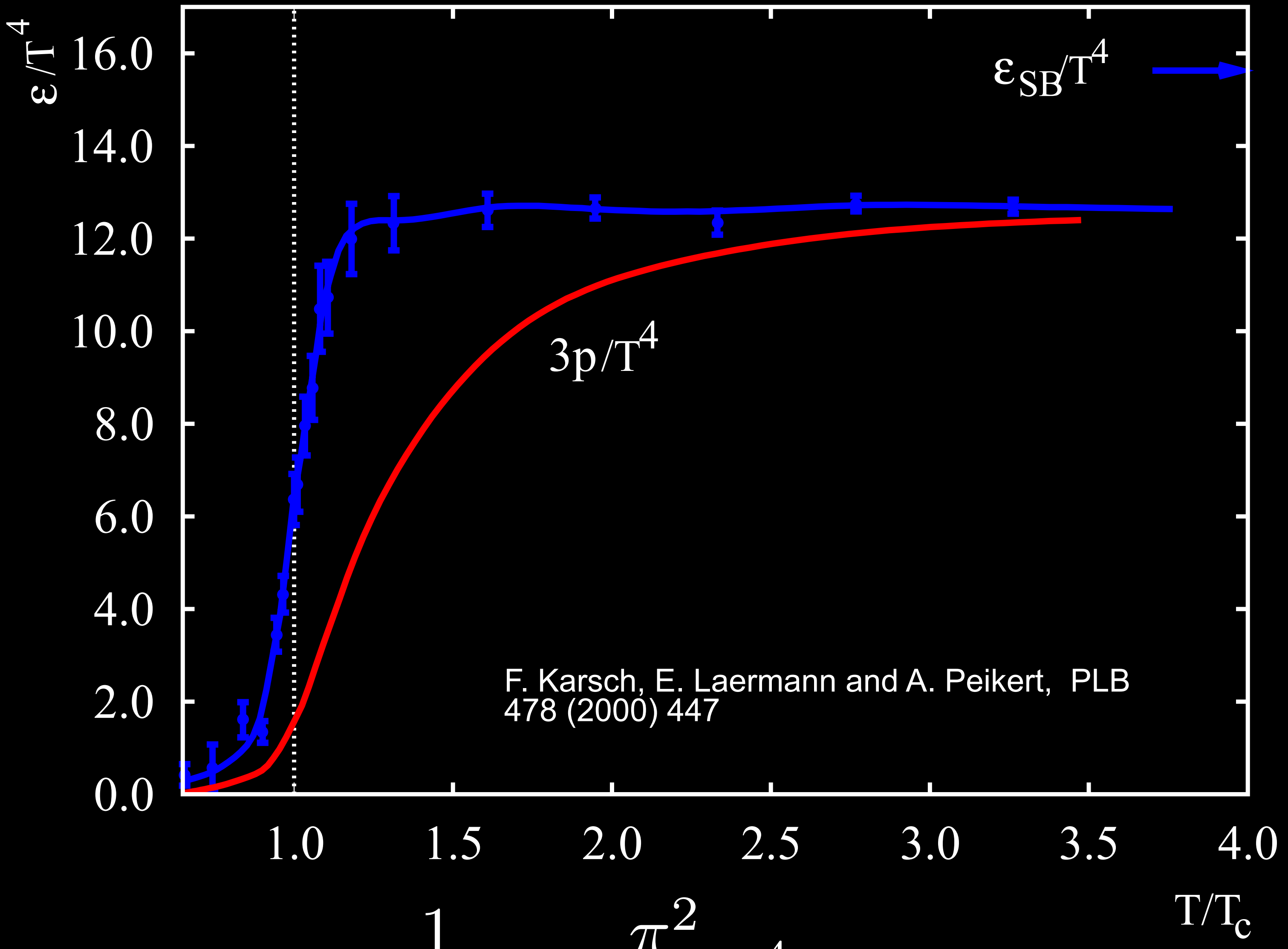
What happens when you heat and compress matter to very high temperatures and densities?

This talk focusses on what we learned at RHIC and the LHC from anisotropic flow



high-p_t physics in the next talk of B. Wyslouch

QCD on the Lattice



F. Karsch, E. Laermann and A. Peikert, PLB 478 (2000) 447

T_C ~ 170 ± 20 MeV, ε_C ~ 0.6 GeV/fm^3

at the critical temperature a strong increase in the degrees of freedom

- ✓ gluons, quarks & color!

at the phase transition dp/dε decreases rapidly

not an ideal massless gas!

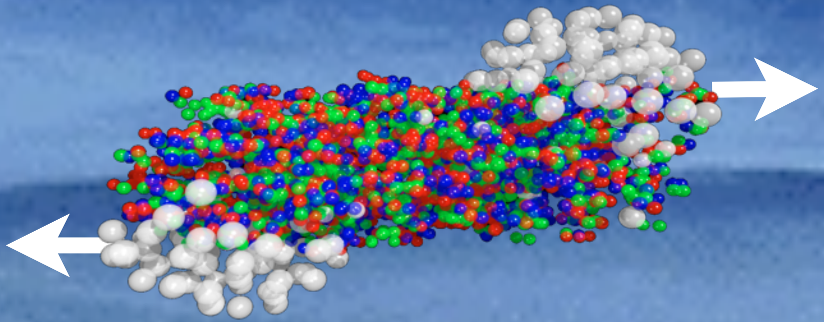
what are the transport properties?

$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

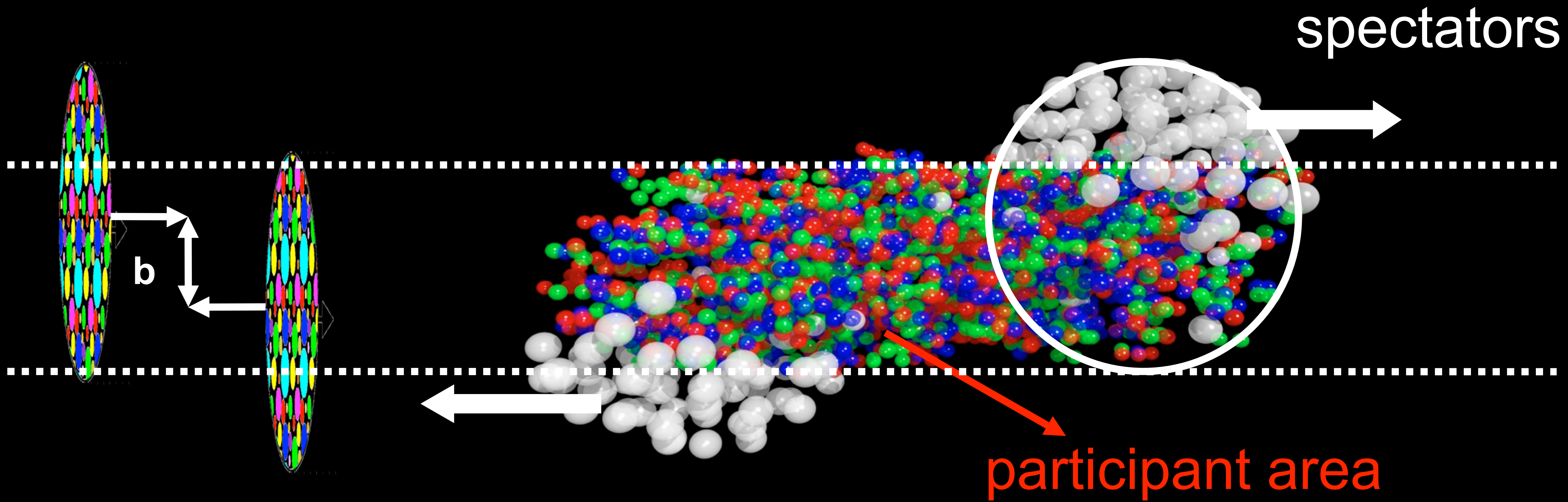
$$g_{\mathrm{H}} \approx 3 \quad g_{\mathrm{QGP}} \approx 37$$

$$g = 2_{\mathrm{spin}} \times 8_{\mathrm{gluons}} + \frac{7}{8} \times 2_{\mathrm{flavors}} \times 2_{q\bar{q}} \times 2_{\mathrm{spin}} \times 3_{\mathrm{color}}$$

study phase transition in controlled lab conditions by colliding heavy-ions

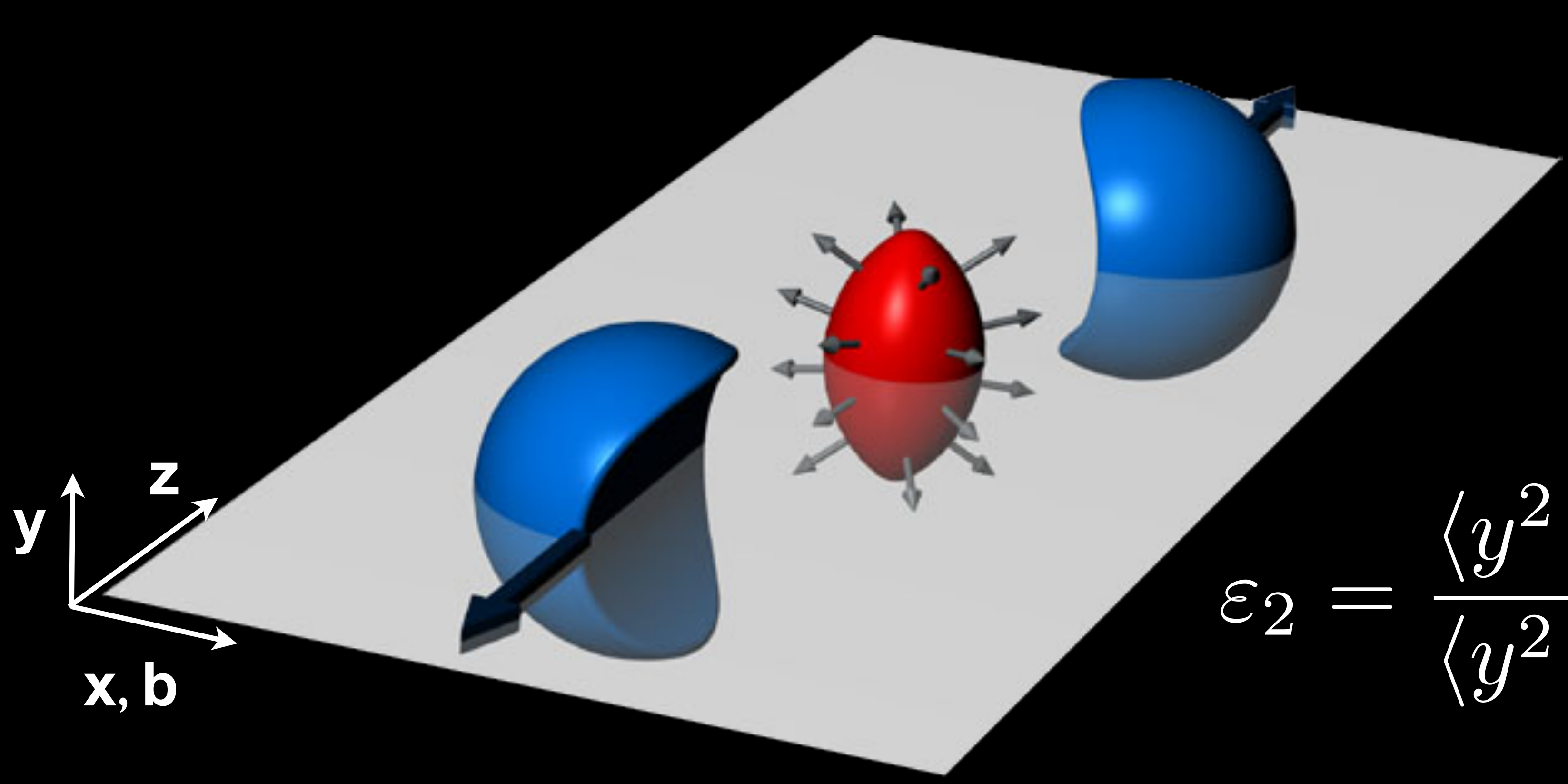


Collision Centrality

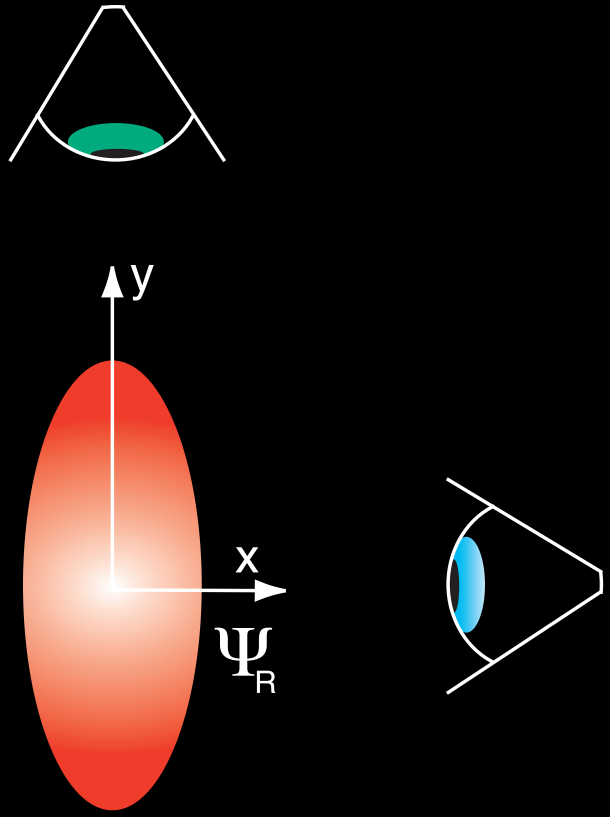


very hot and dense nuclear matter in more central collisions while we approach "simple" nucleon-nucleon collisions in very peripheral collisions

The Reaction Plane



$$\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

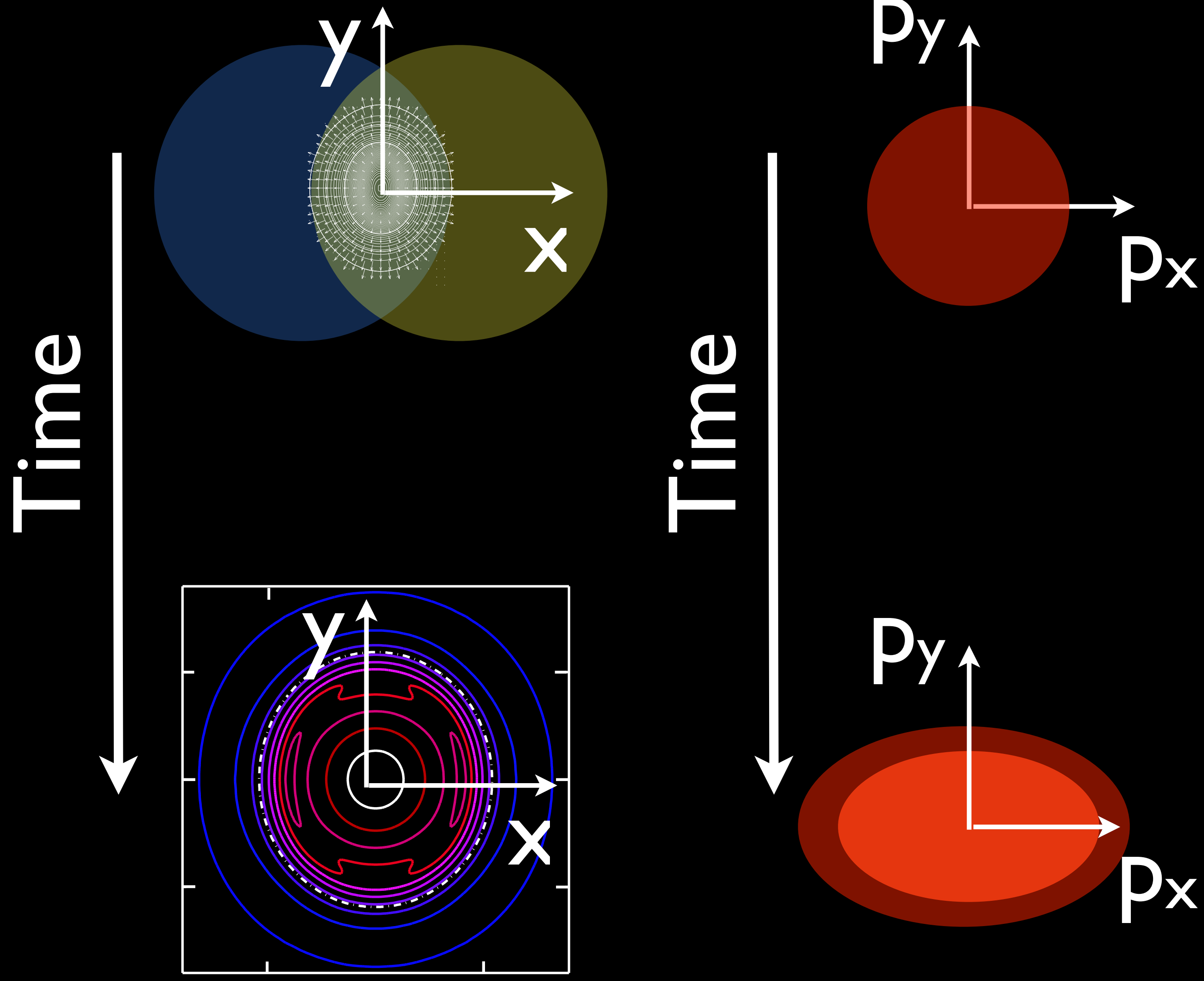


in non-central collisions the participant area is not azimuthally symmetric

Elliptic Flow

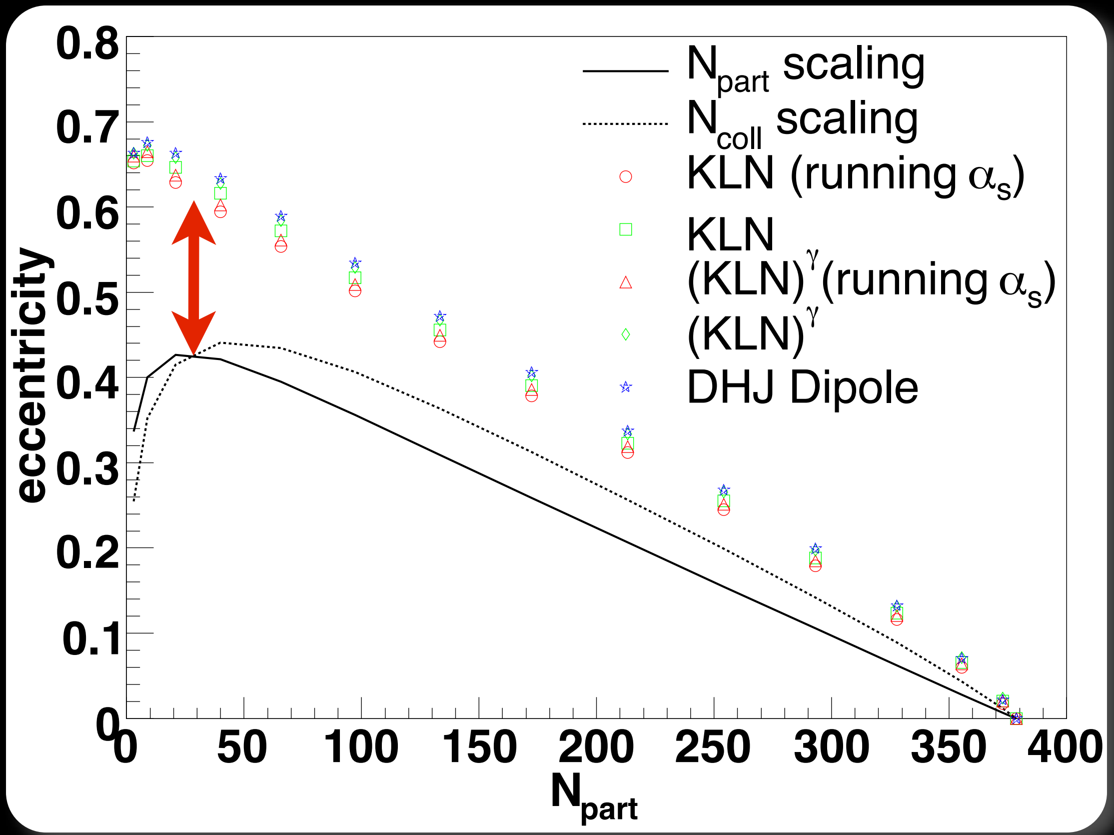
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\phi \rangle$$

- in non central collisions coordinate space configuration is anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric)
- interactions among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy → anisotropic flow
- self-quenching → sensitive to early stage

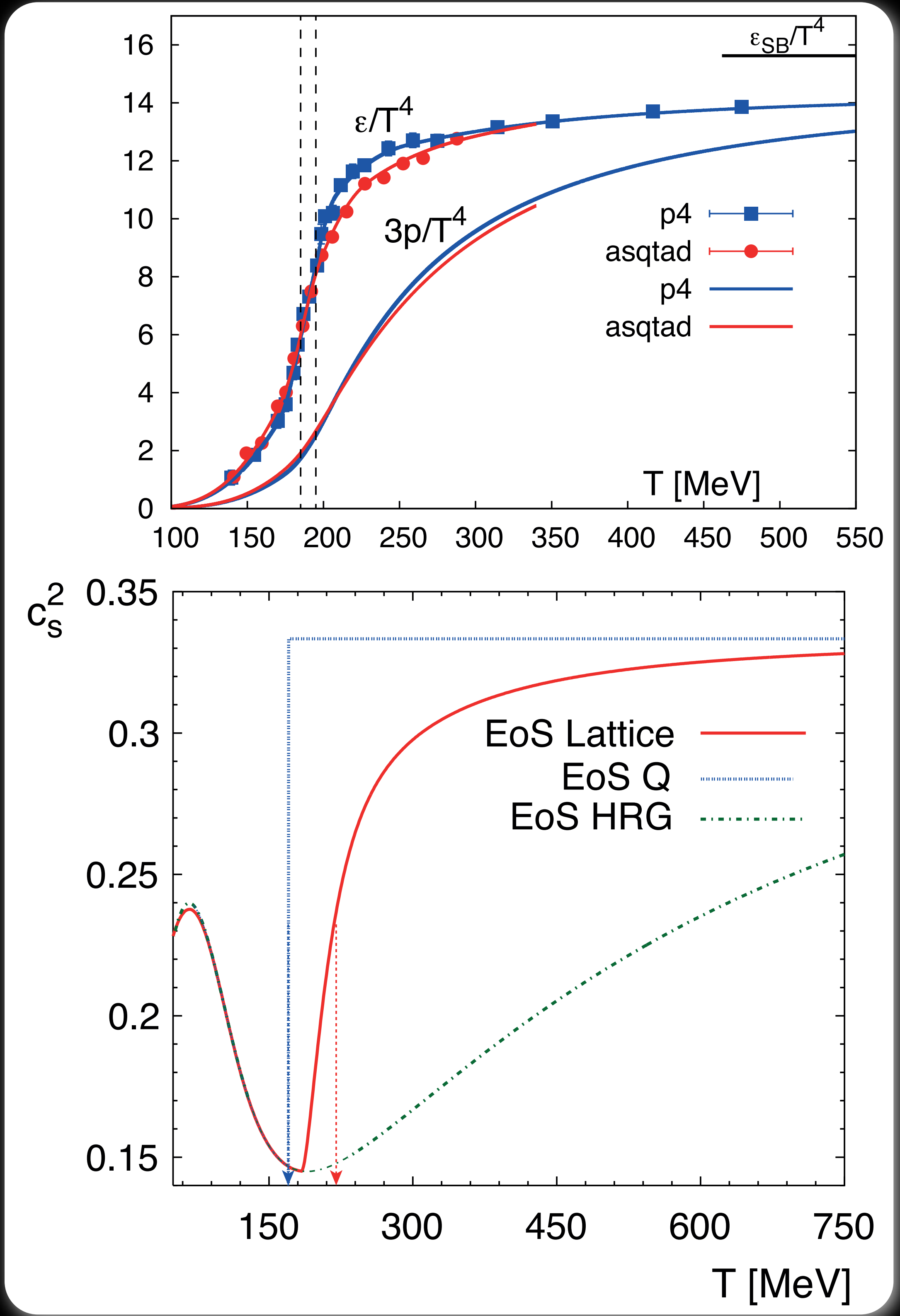


Elliptic Flow

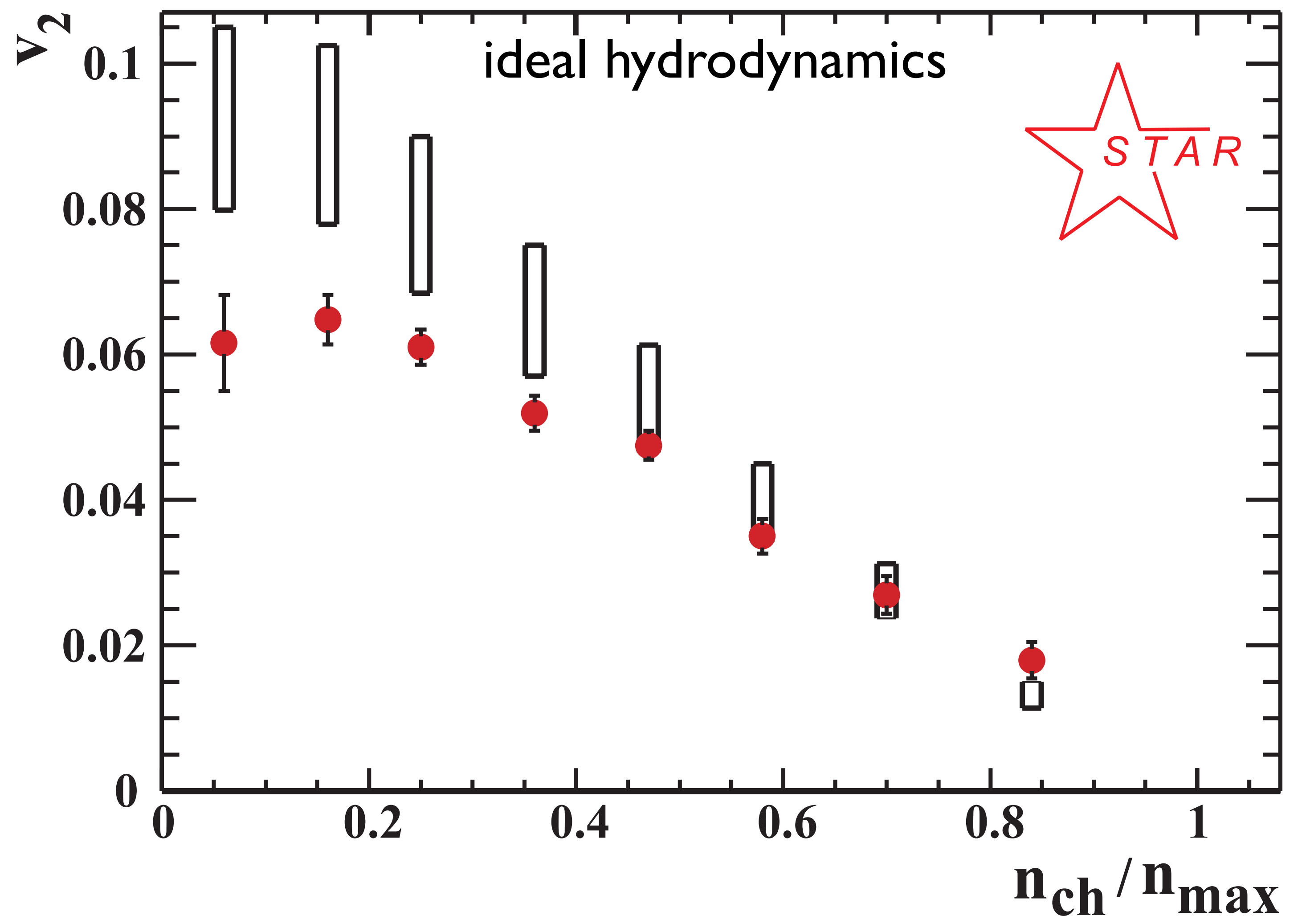
Elliptic flow v_2 depends on fluid properties: the EoS via $c_s^2 = \dfrac{\partial p}{\partial \varepsilon}$, shear viscosity over entropy ratio η/s but also on: initial conditions: particular initial spatial eccentricity ε_2



H-J. Drescher et al., Phys.Rev.C74:044905,2006



Elliptic Flow at RHIC



STAR Phys. Rev. Lett. 86, 402–407 (2001)

for an ideal gas the elliptic flow would be almost zero while the observed elliptic flow is large

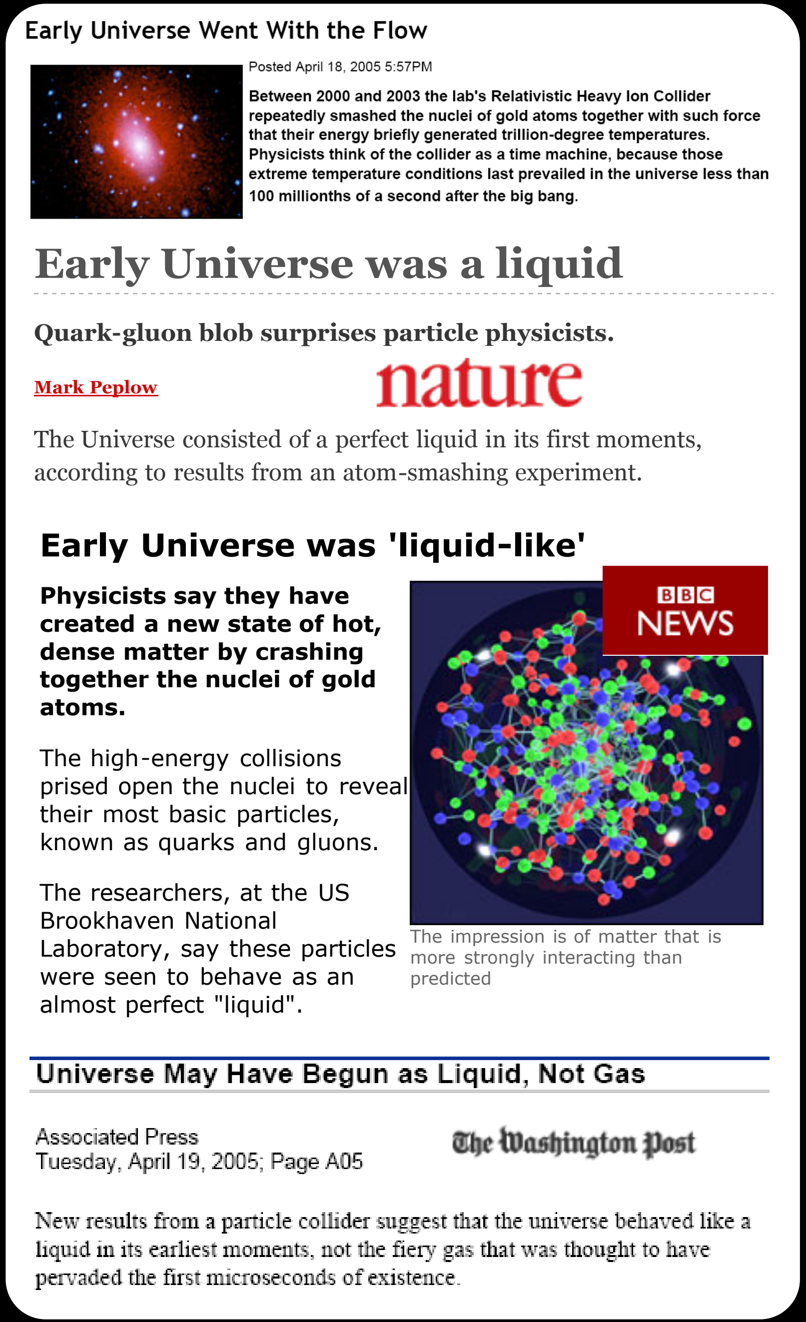
ideal hydro ($\eta/s=0$) predicts the v_2 magnitude for more central collisions

system behaves like an an almost ideal liquid, not an ideal gas!

RHIC Scientists Serve Up “Perfect” Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005



Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

nature

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Early Universe was 'liquid-like'

BBC NEWS

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

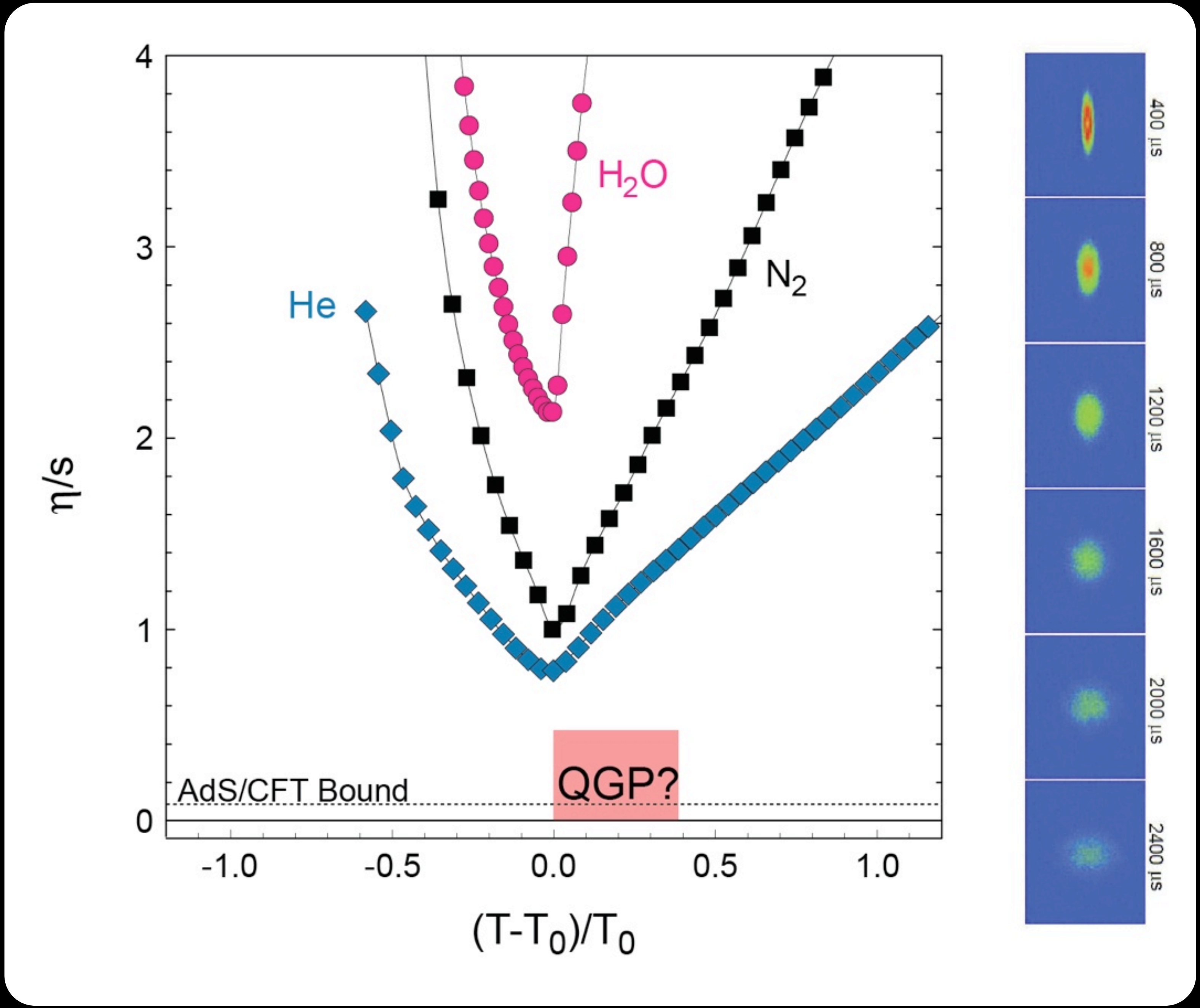
The impression is of matter that is more strongly interacting than predicted

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

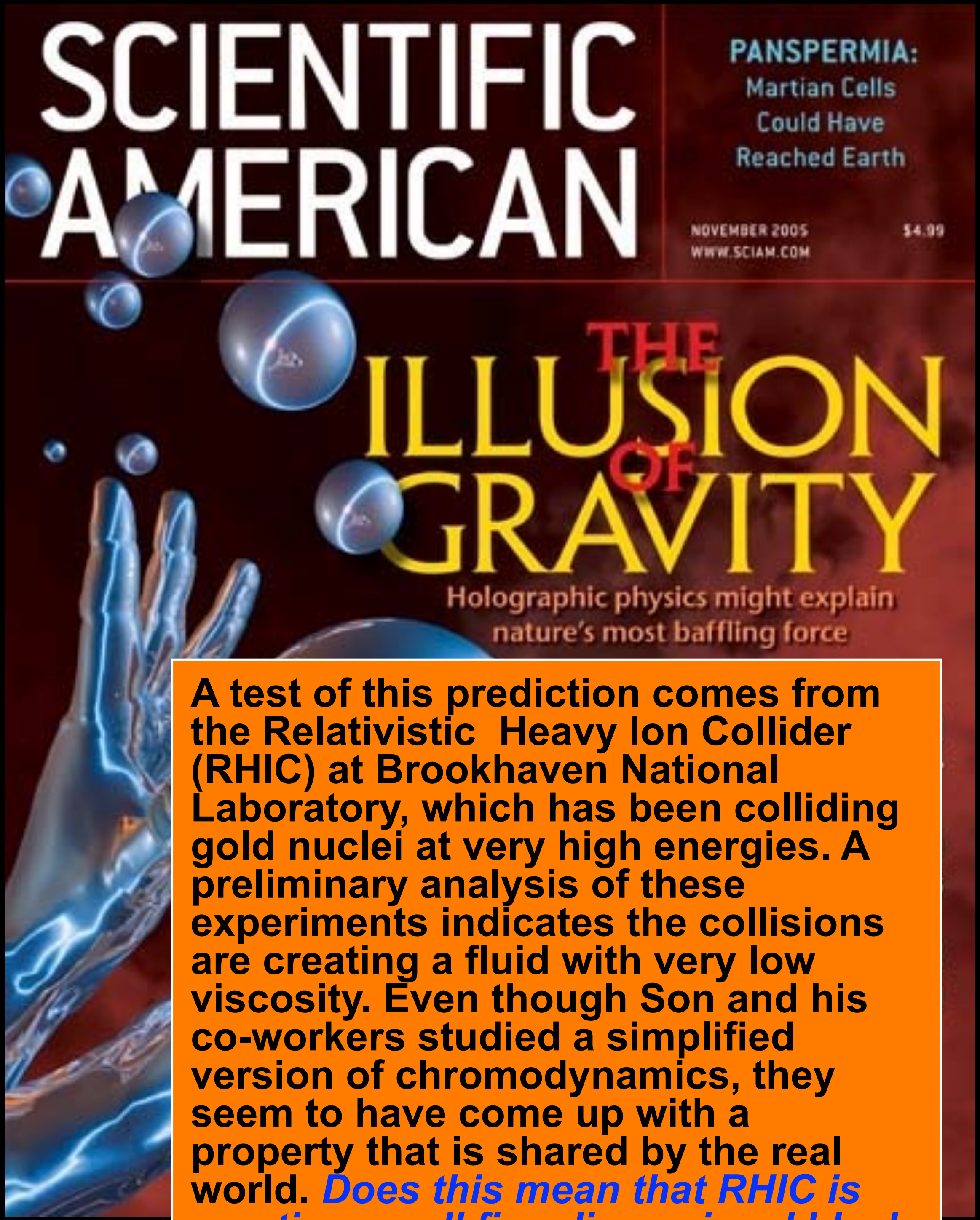


from AdS/CFT to cold atoms

η/s?

- good fluids in nature have a kinematic viscosity η/s of order $\hbar/k_B$
- calculable in perturbative QCD: $\eta/s \sim 1/g^4 \ln(1/g)$
- calculable in a N=4 Super Yang Mills theory with large number of colors using a gauge gravity duality
  - $\eta/s = \hbar/4\pi k$

“The Illusion of Gravity” J. Maldacena



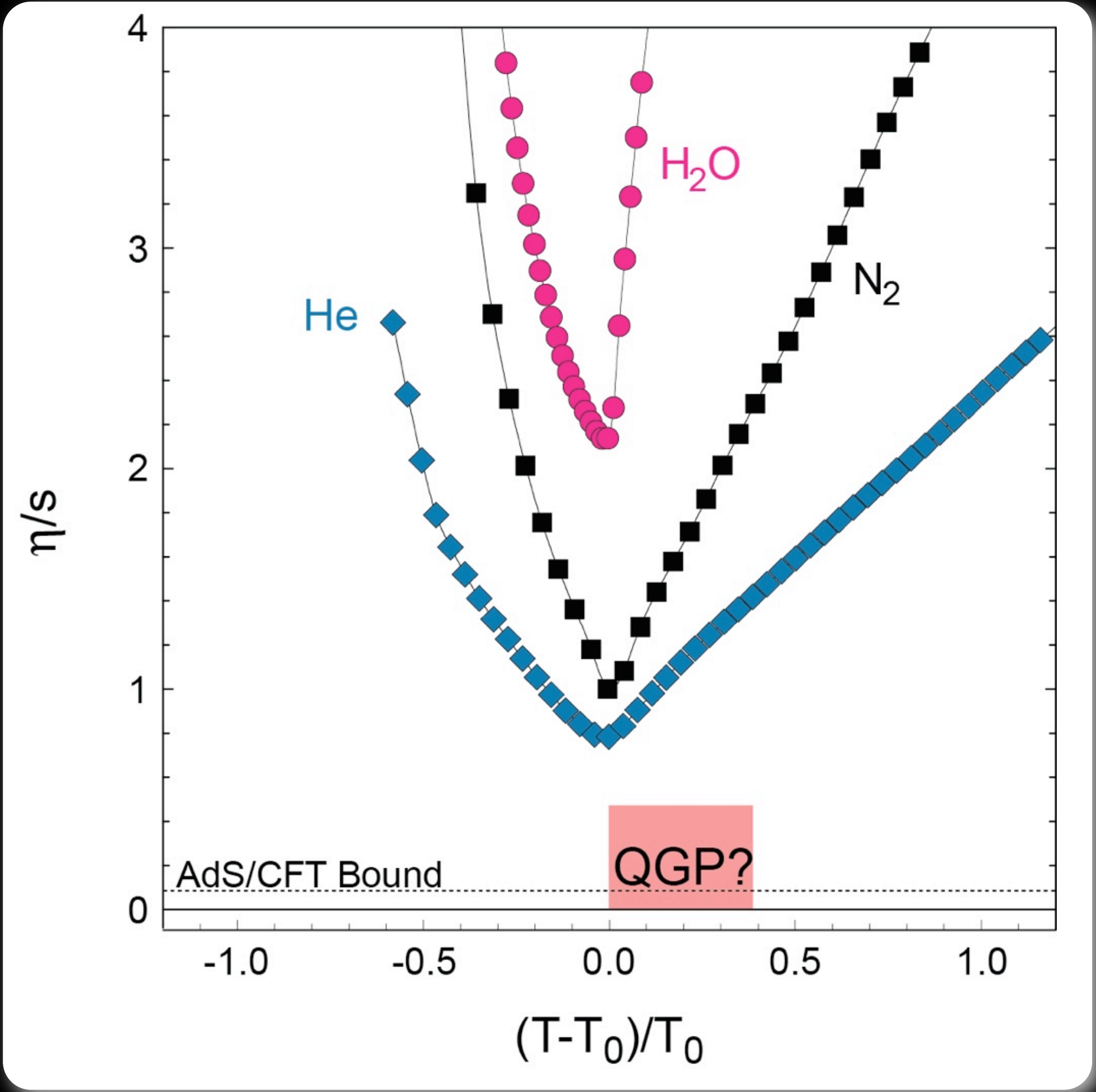
A test of this prediction comes from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, which has been colliding gold nuclei at very high energies. A preliminary analysis of these experiments indicates the collisions are creating a fluid with very low viscosity. Even though Son and his co-workers studied a simplified version of chromodynamics, they seem to have come up with a property that is shared by the real world. *Does this mean that RHIC is creating small five-dimensional black holes? It is really too early to tell,* both experimentally and theoretically.

The Perfect Liquid?

model calculations suggest that the RHIC v_2 results are close to the ideal hydrodynamical limit.

these calculations place an upper limit on η/s which is smaller than ~ 4 x AdS/CFT bound

main uncertainties on η/s due to uncertainties in the initial conditions and the unknown dependence of η/s versus temperature

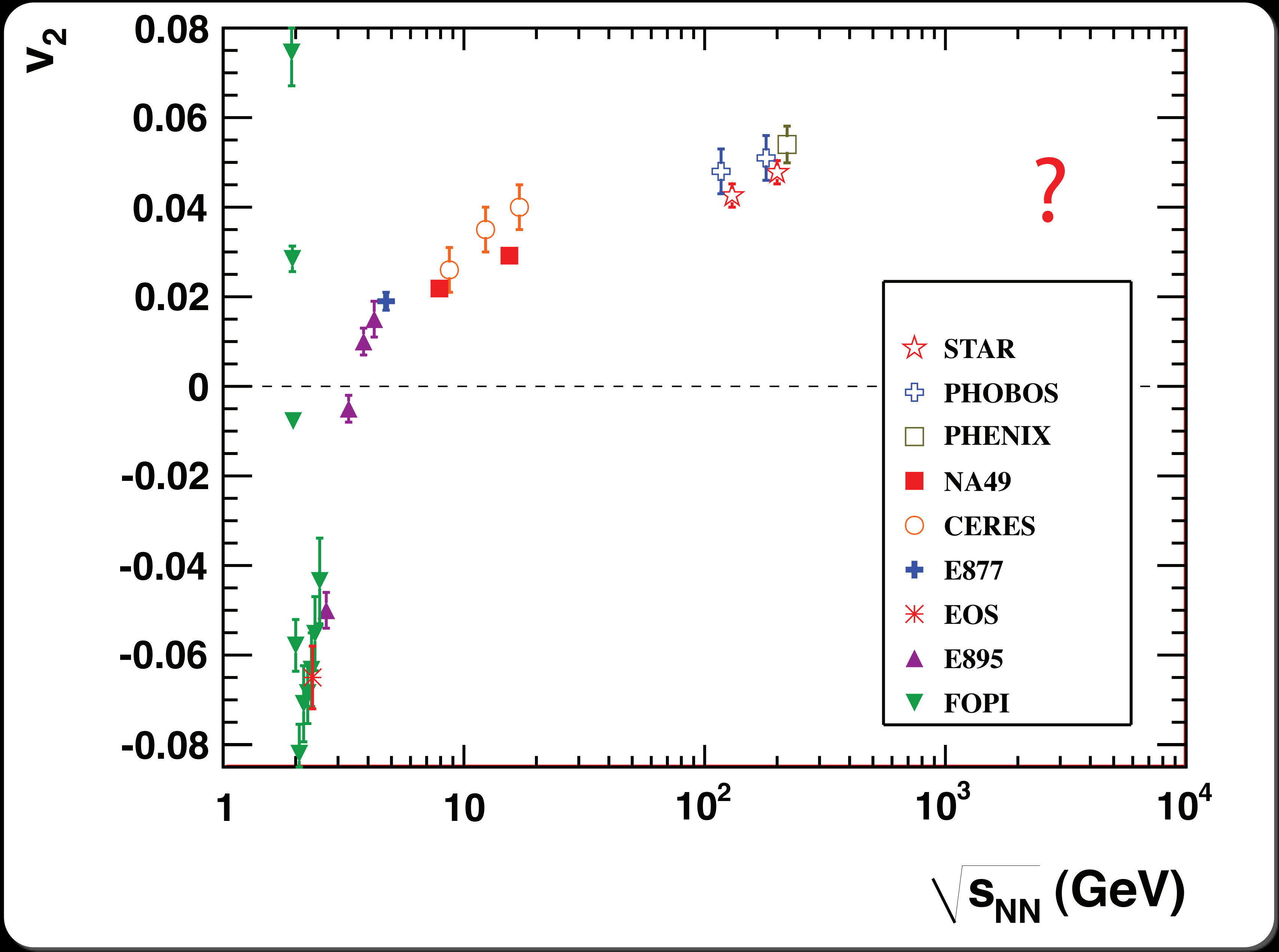


Based on R. Lacey et al., Phys.Rev.Lett.98:092301,2007.

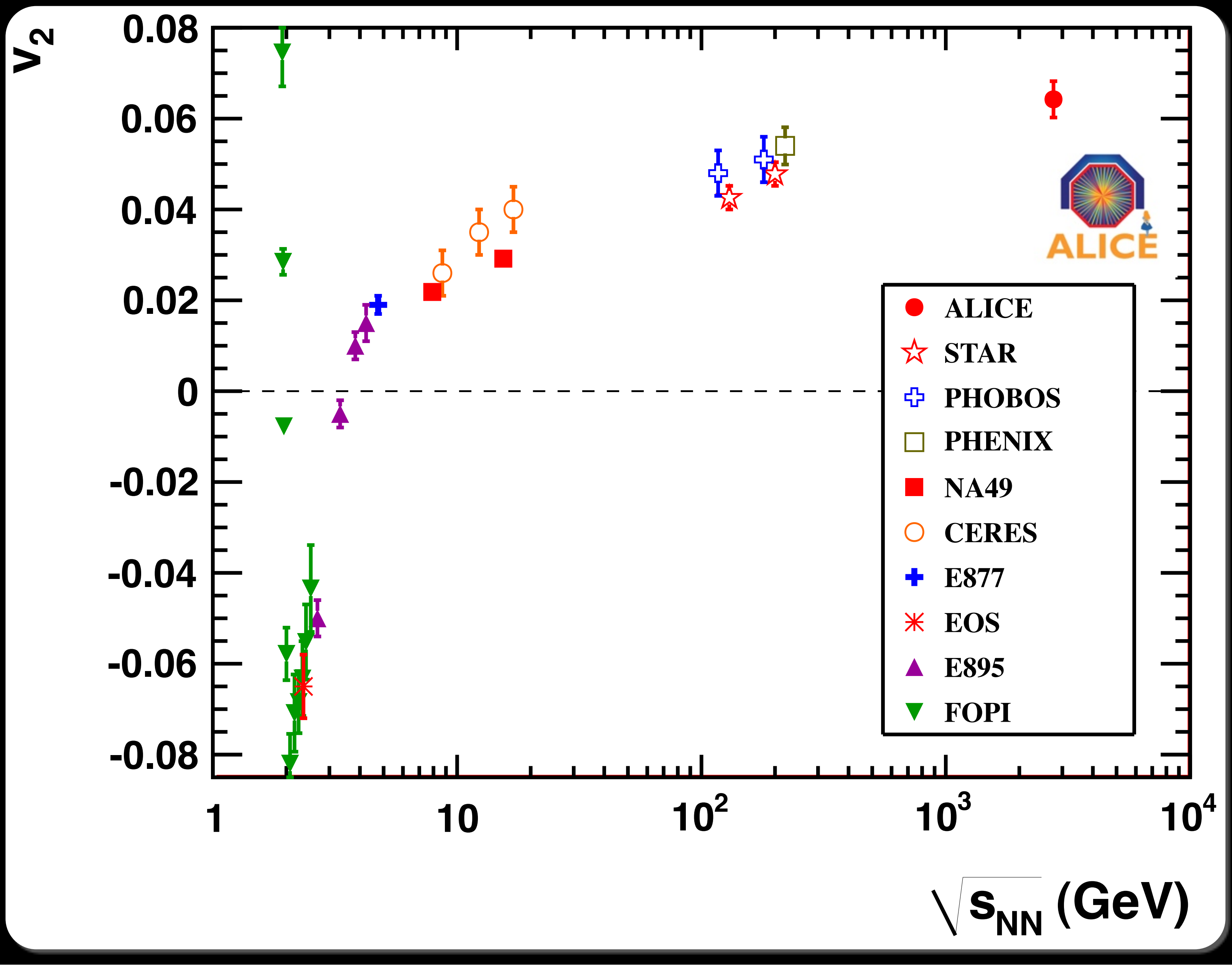
The Perfect Liquid?

What to expect at the LHC: still the perfect liquid or are we approaching the viscous ideal gas?

Can we get better constraints on η/s (constrain initial conditions and temperature dependence of η/s)?



The Perfect Liquid

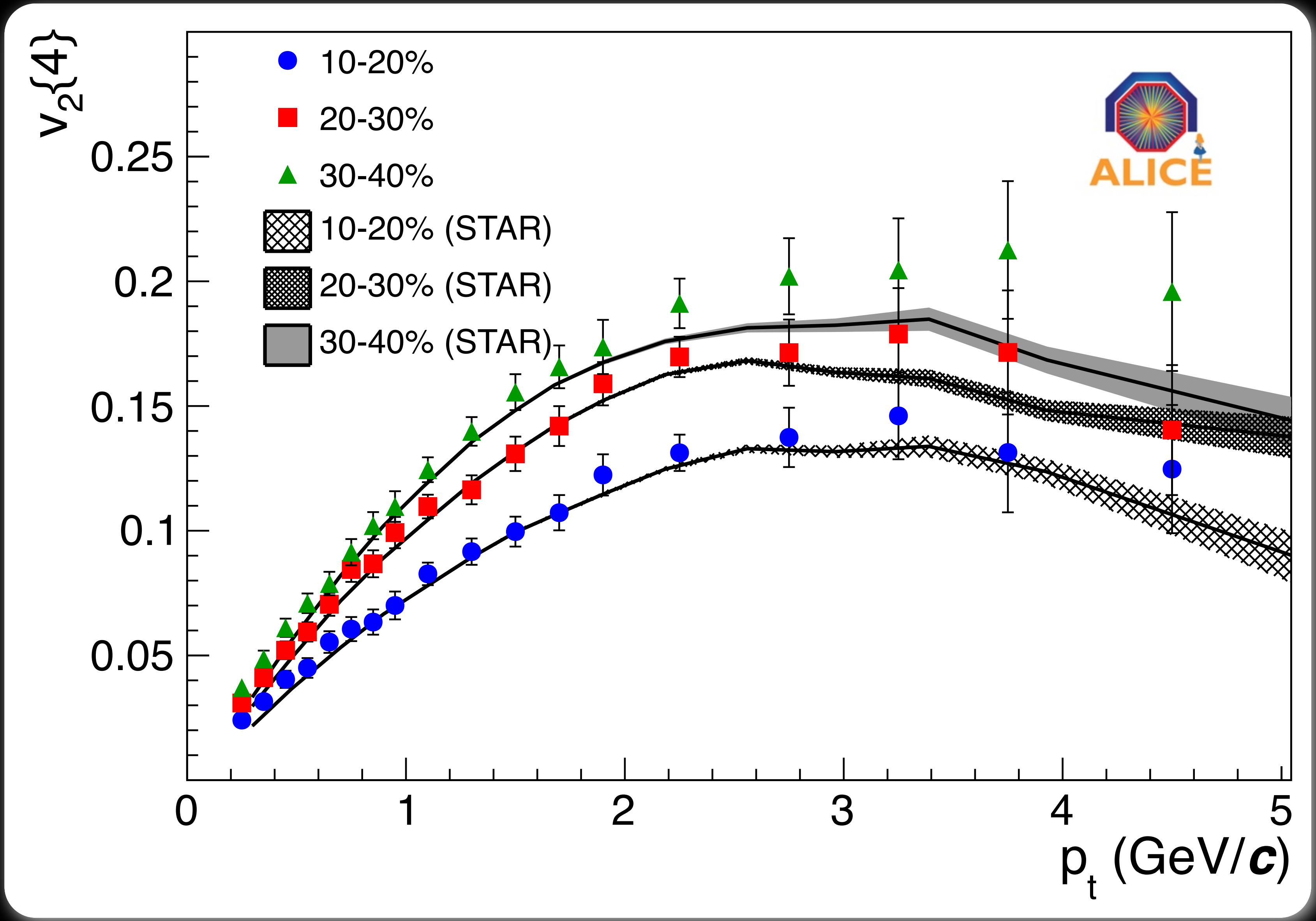


K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)

The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid), constraints dependence of η/s versus temperature

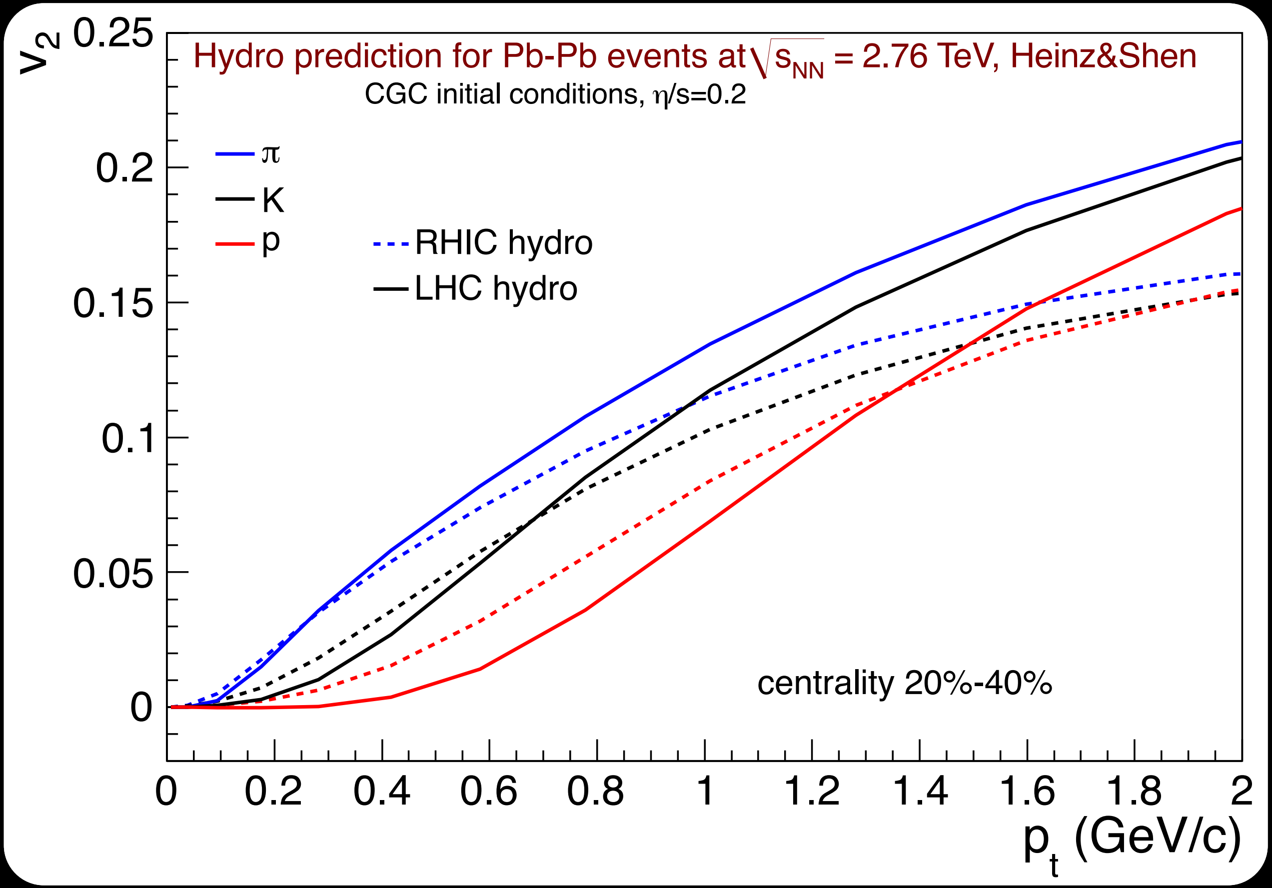
v_2 as function of p_t

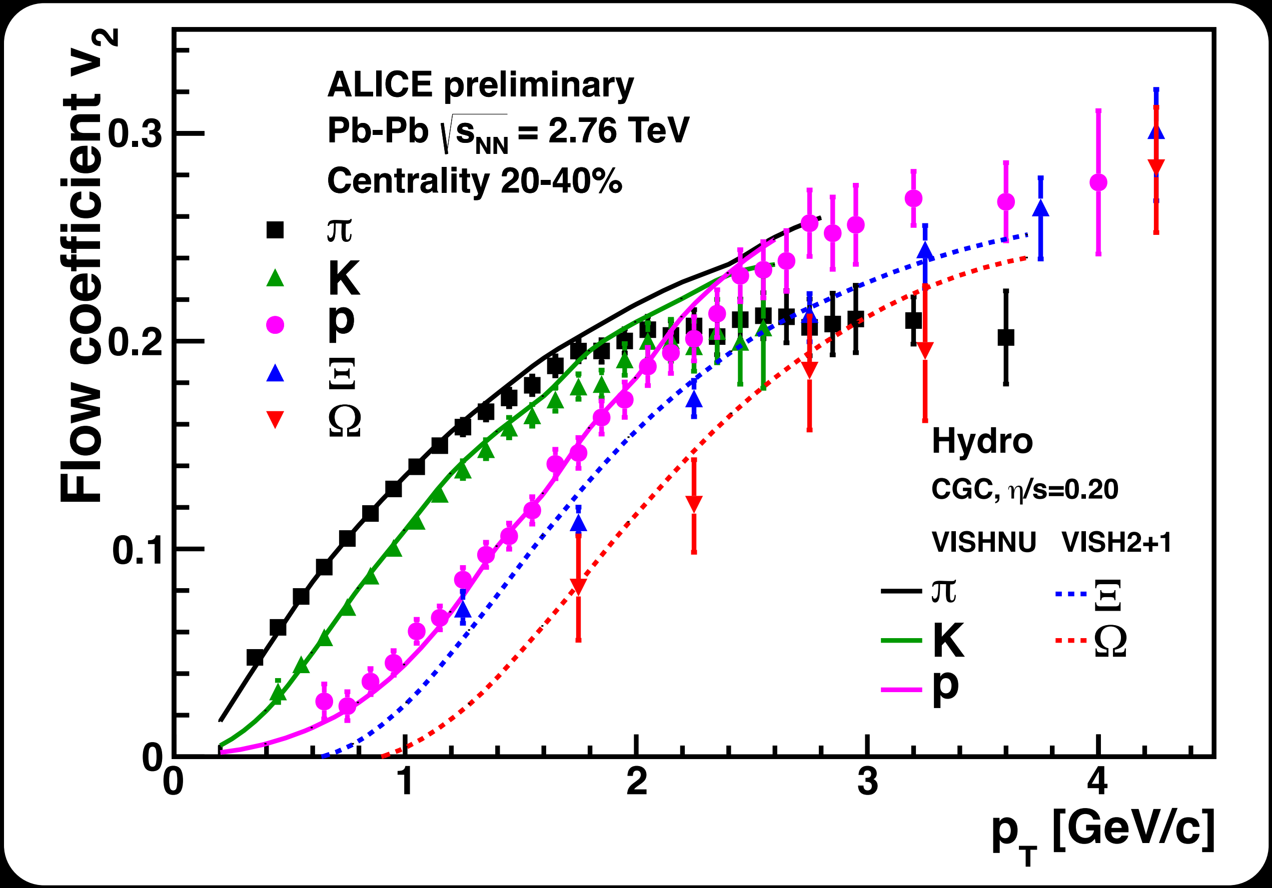
K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)



Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that from hydro?

v_2 for identified particles

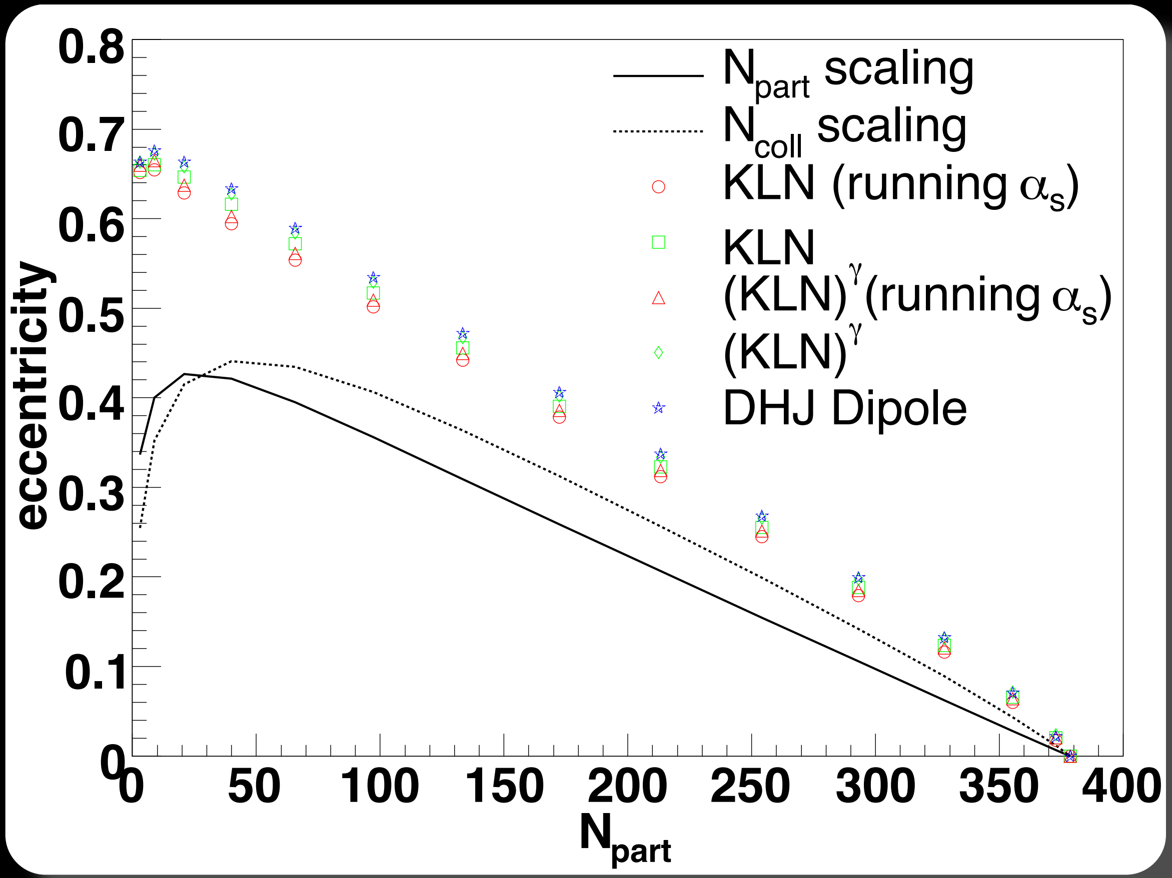




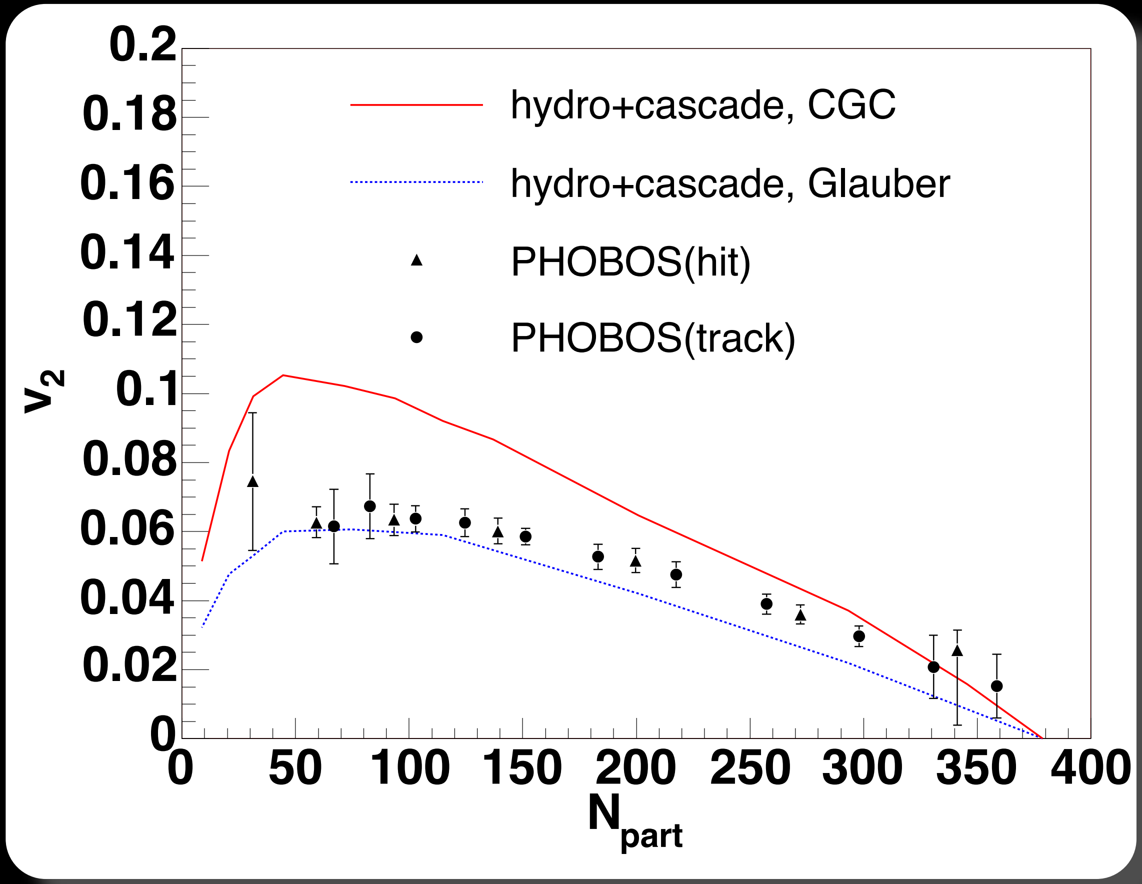
Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

hydro models predict larger mass splitting
data follows this mass splitting and agrees well with
hydro predictions for mid-central collisions

Better constraints on η/s (understanding the initial conditions)



H-J. Drescher et al., Phys.Rev.C74:044905,2006



T. Hirano et al., Phys. Lett. B 636 299 (2006)
T. Hirano et al., J.Phys.G34:S879-882,2007

$$v_2 \propto \varepsilon$$

- Estimates of the eccentricity vary significantly ~ 30%!
- Leads to large uncertainty in estimate of η/s

Flow Fluctuations

in limit of small (not necessarily Gaussian) fluctuations

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

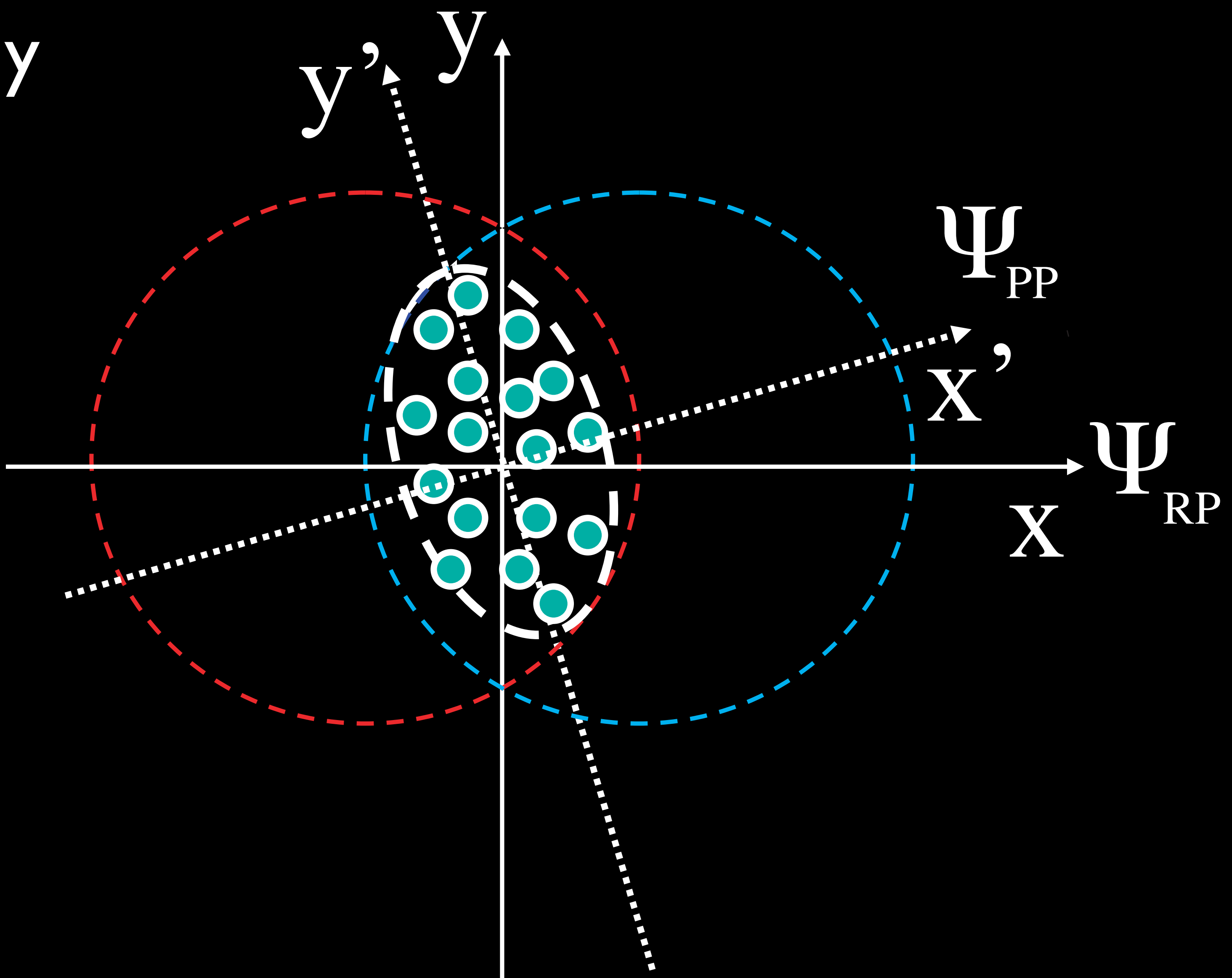
$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$

$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

in limit of only (Gaussian)fluctuations

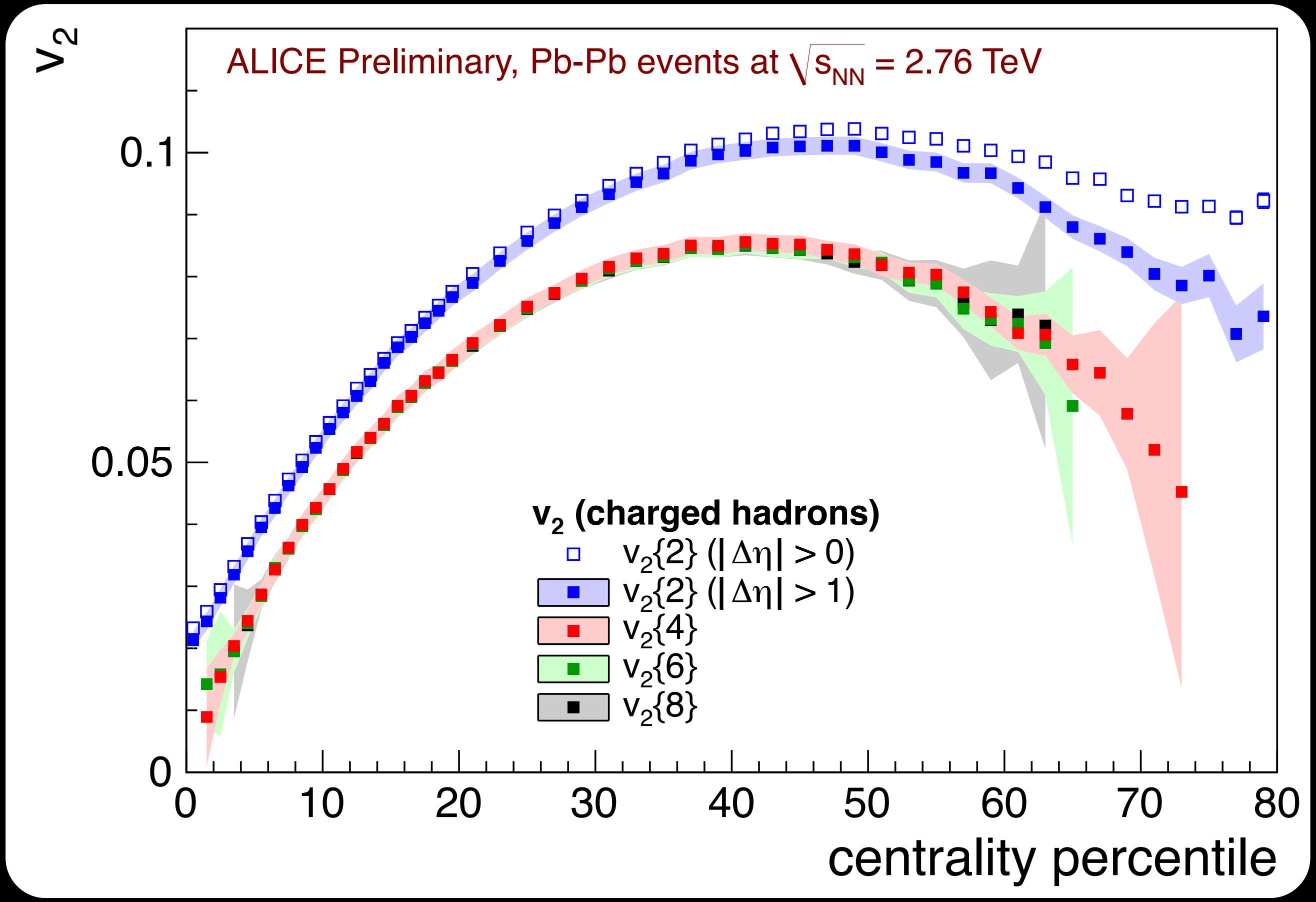
$$v_n\{4\} = 0$$

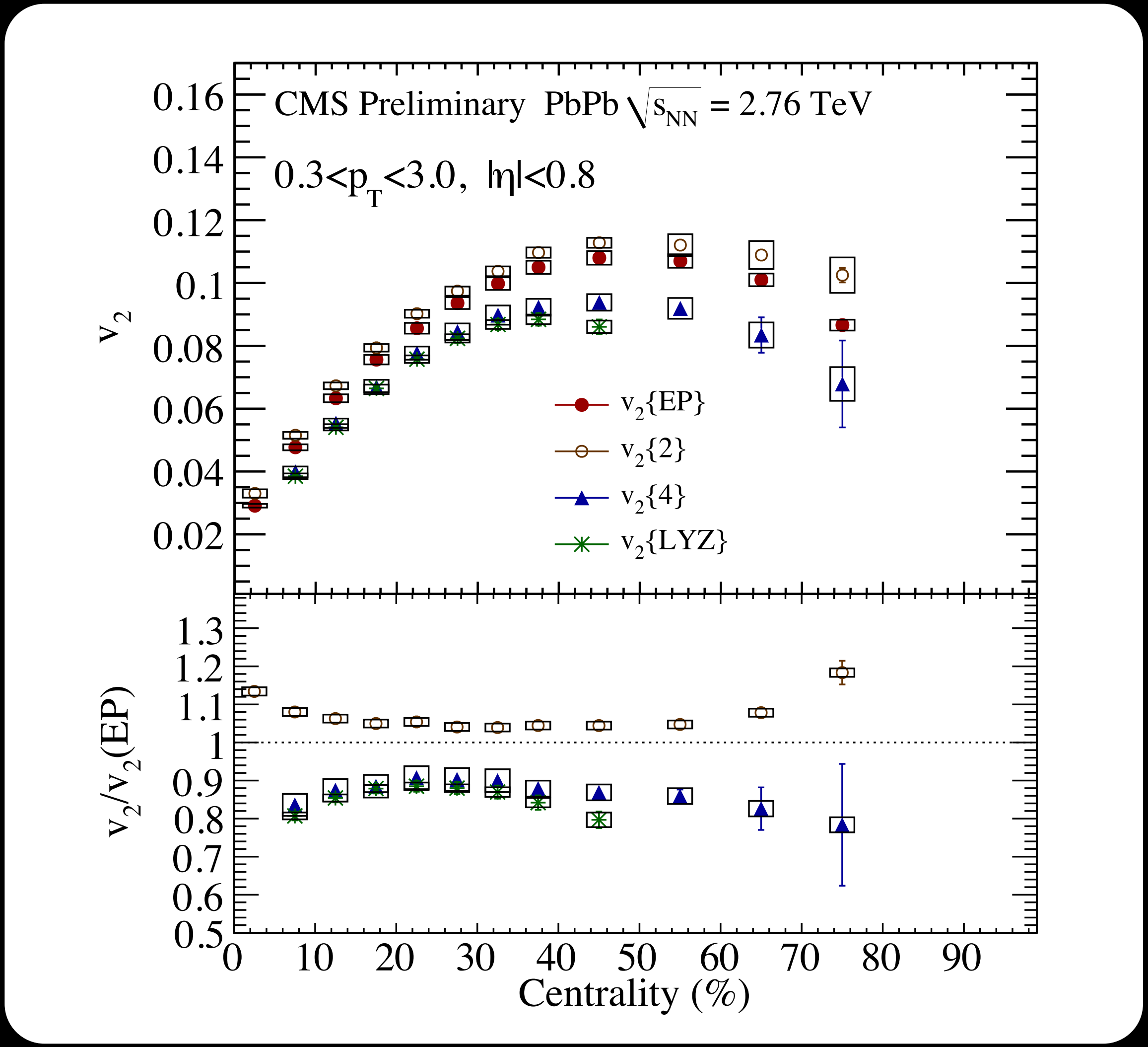
$$v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$$



eccentricity fluctuations:
M. Miller and RS, arXiv:nucl-ex/0312008 (2003)
participant eccentricity
PHOBOS QM2005: Nucl. Phys. A774: 523 (2006)

v_2 Fluctuations

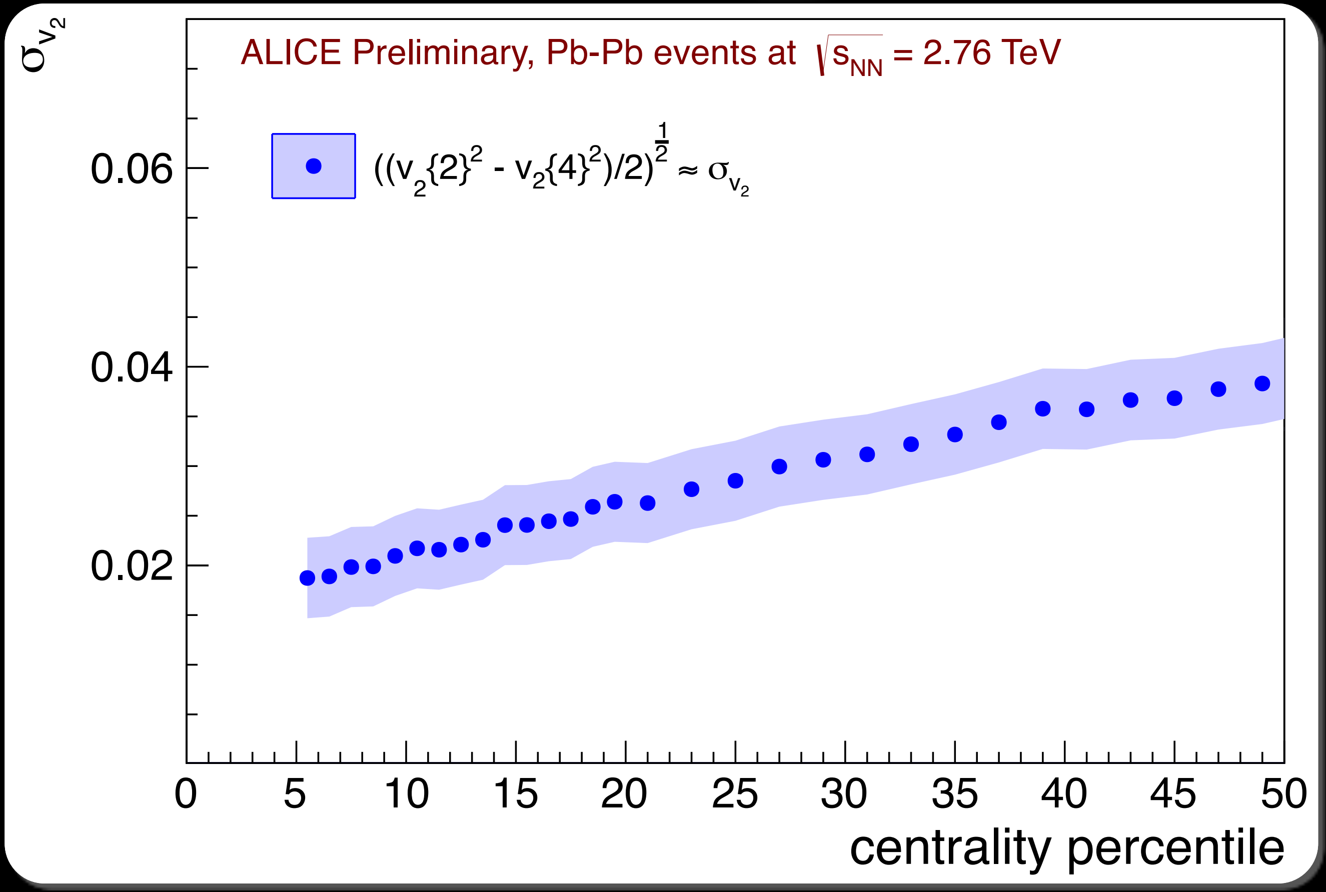


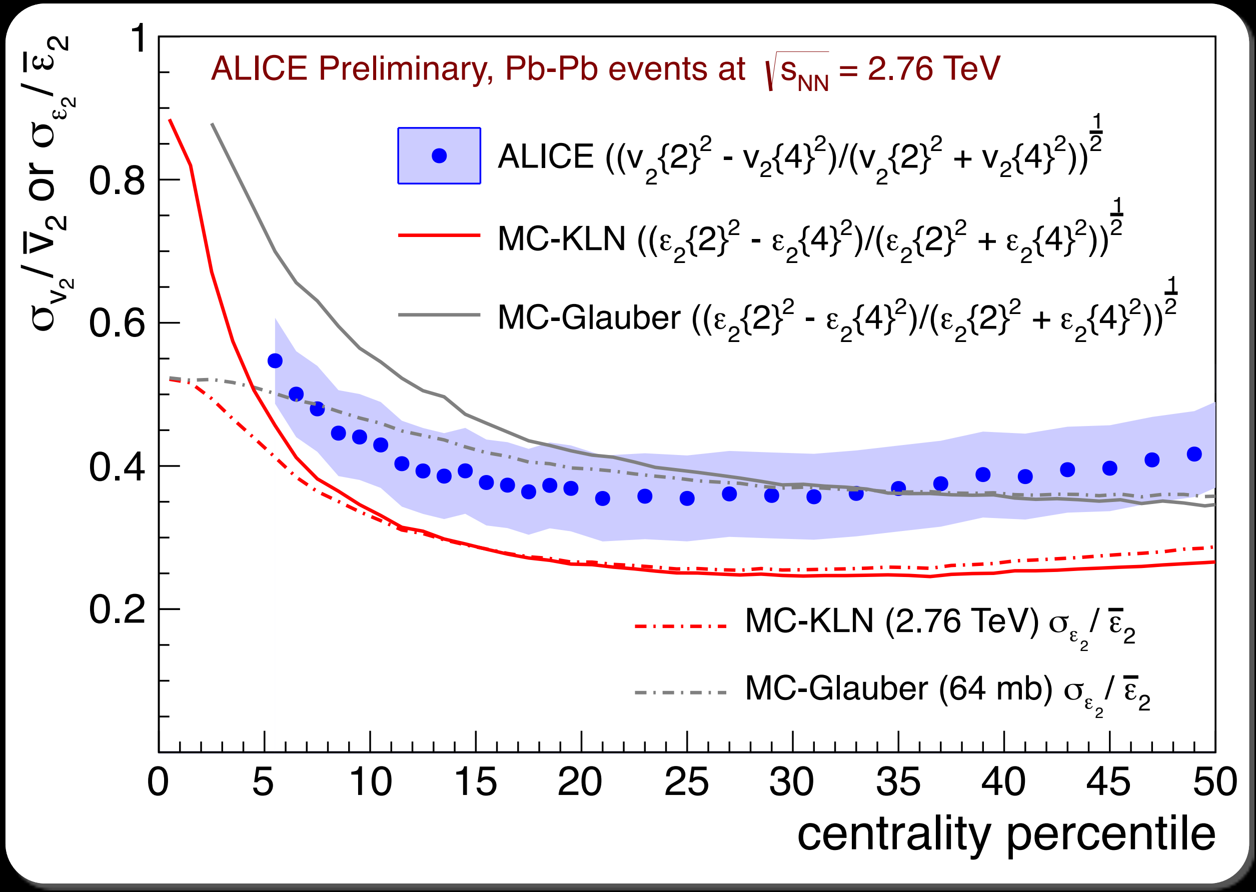


CMS PAS HIN-10-002

behavior as expected when correlations are dominated by collective flow (difference between two- and multi-particle estimates mainly due to e-by-e fluctuations in the flow

v_2 Fluctuations



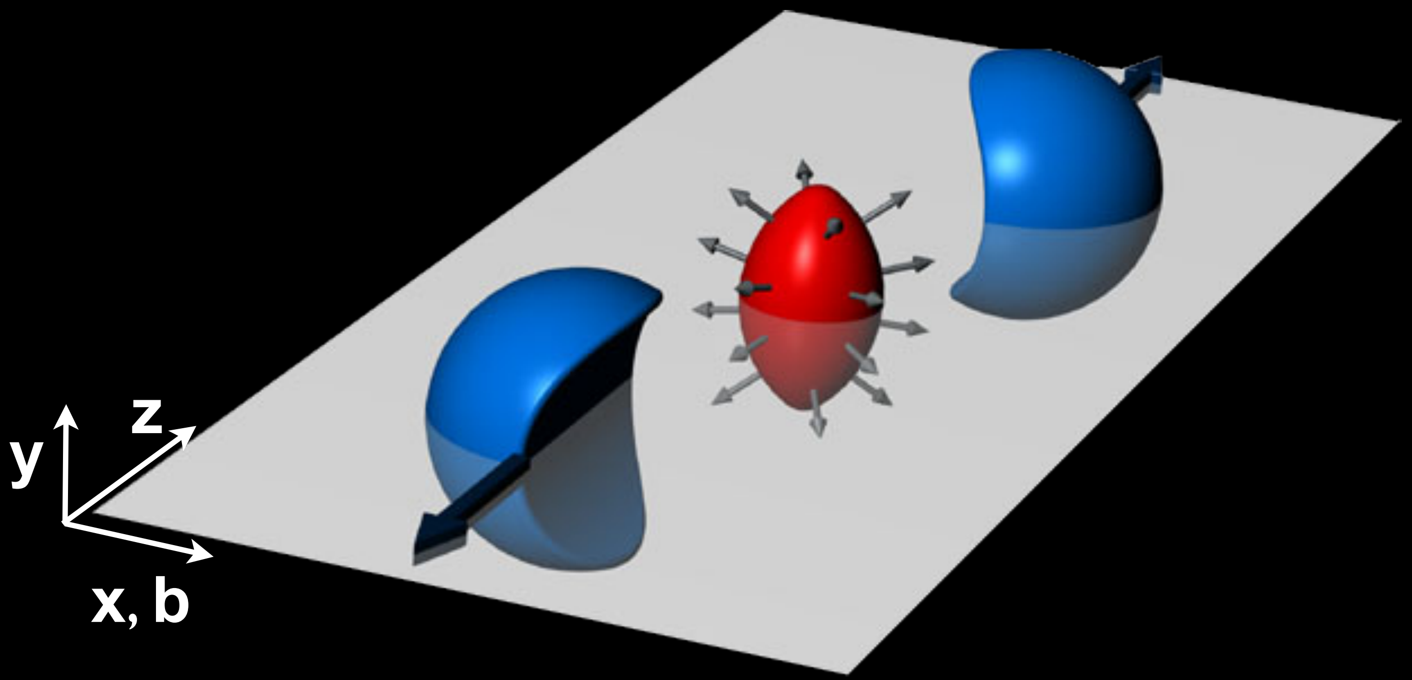


$$\sigma_{v_n} \simeq [\frac{1}{2}(v_n^2\{2\} - v_n^2\{4\})]^{\frac{1}{2}}$$

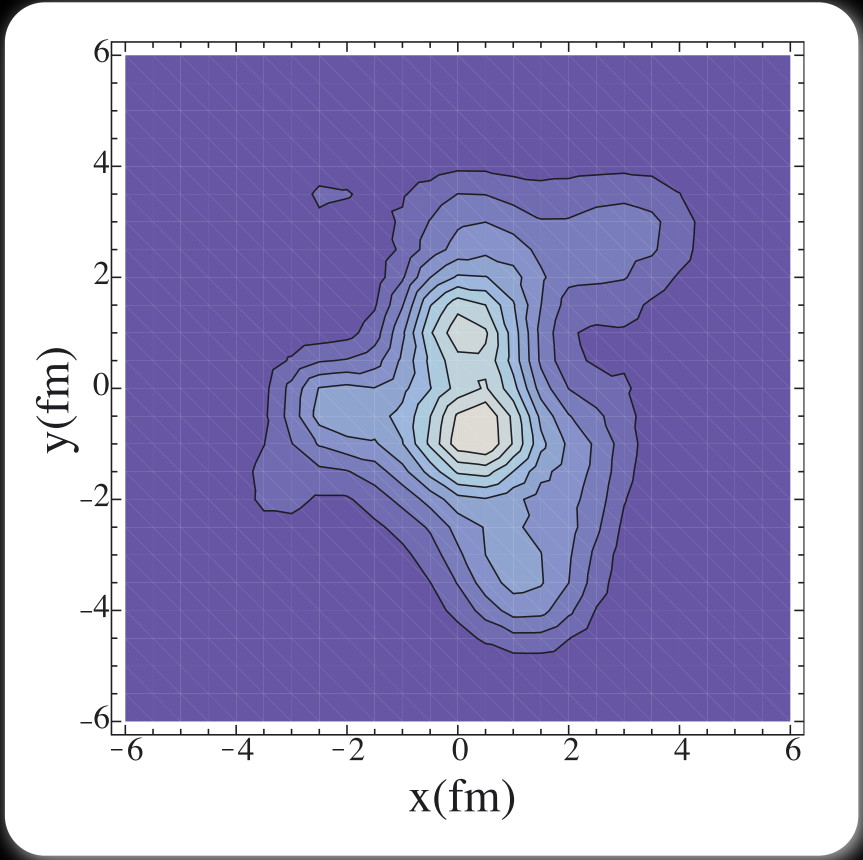
$$\frac{\sigma_{v_n}}{\bar{v}_n} \simeq \left(\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right)^{\frac{1}{2}}$$

Fluctuations are significant and are for more central collisions not in agreement with the eccentricity fluctuations in MC-Glauber and MC-KLN CGC

Anisotropic Flow v_n



G. Qin, H. Petersen, S. Bass, and B. Muller



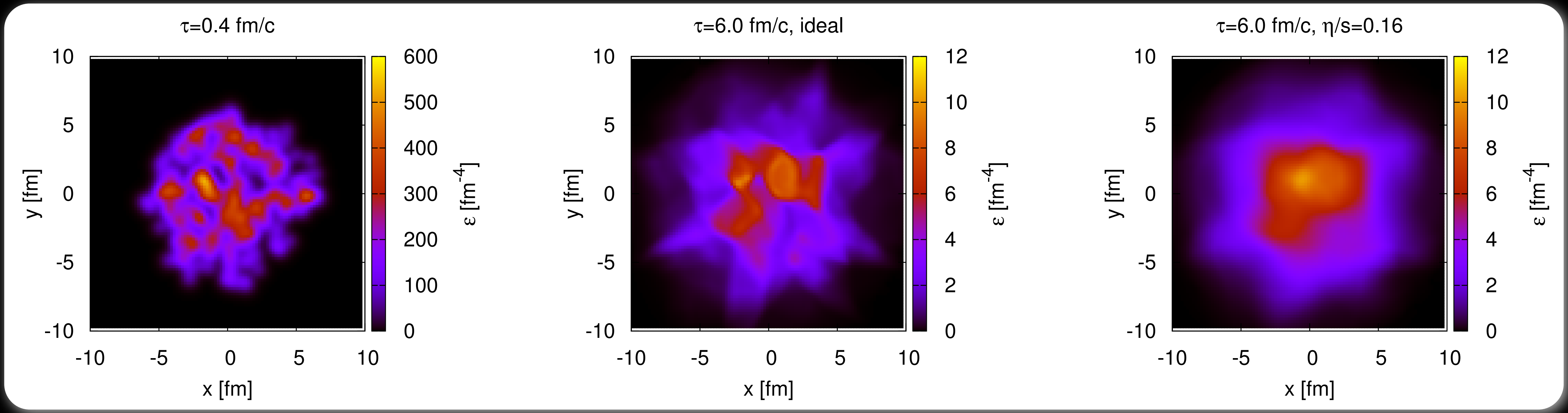
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=2,4,6,\ldots}^{\infty} 2v_n \cos n(\phi - \Psi_R)$$

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)$$

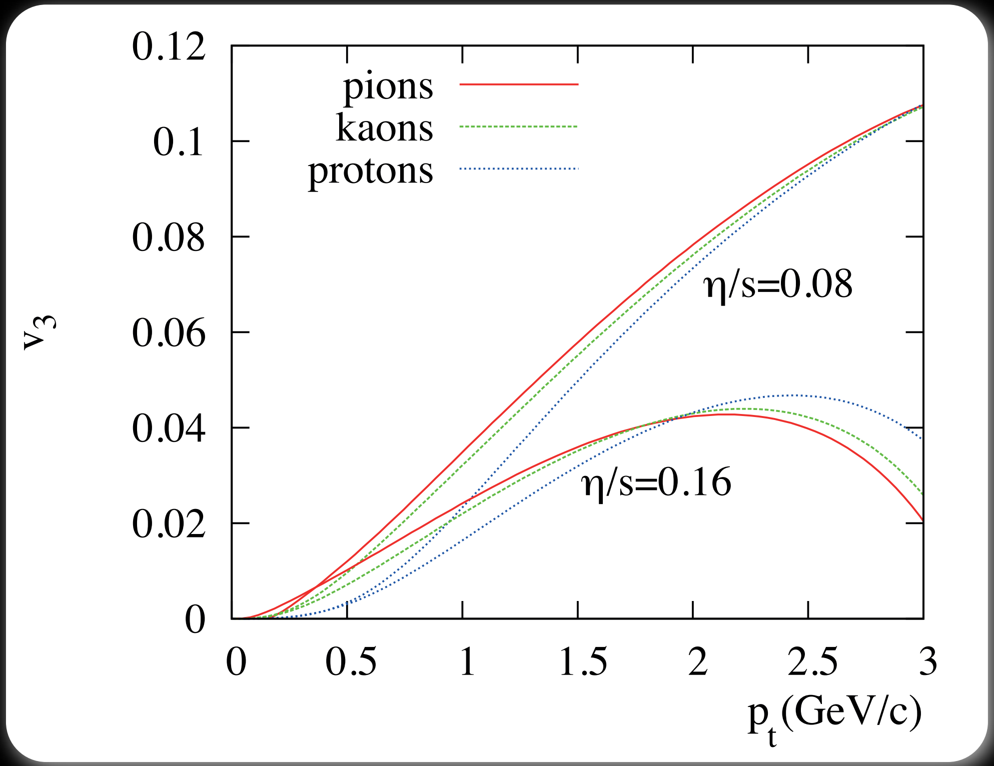
initial spatial geometry not a smooth almond event-by-event (for which all odd harmonics and sin $n(\Phi-\psi_R)$ are zero due to symmetry) may give rise to higher odd harmonics and symmetry planes in momentum space (detailed probes of initial conditions)

Shear Viscosity

Music, Sangyong Jeon



initial conditions ideal hydro $\eta/s=0$ viscous hydro $\eta/s=0.16$



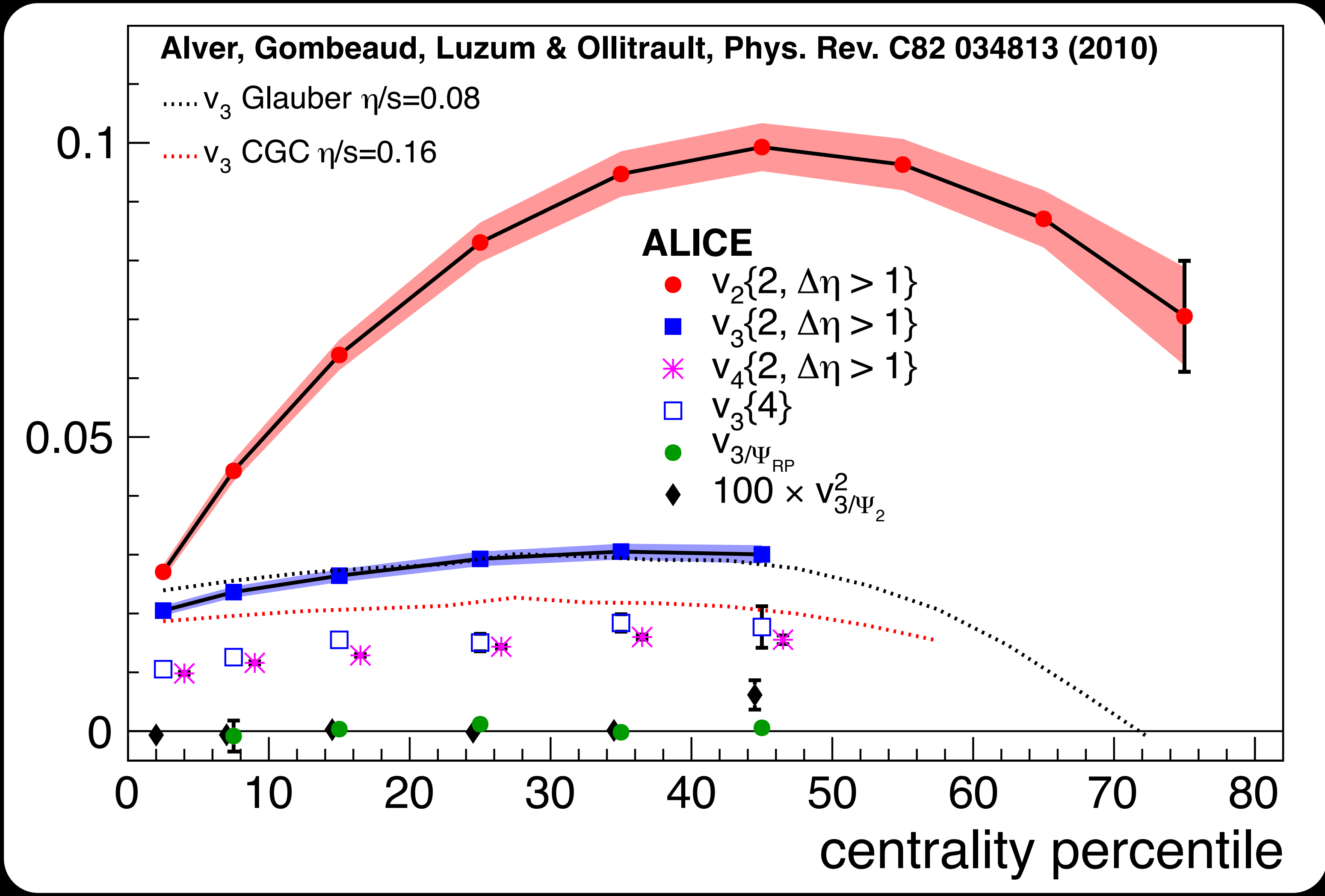
Larger η/s clearly smoothes the distributions and suppresses the higher harmonics (e.g. v_3)

Hydro: Alver, Gombeaud, Luzum & Ollitrault, Phys. Rev. C82 (2010)

the v_n's

The v_3 with respect to the reaction plane determined in the ZDC and with the v_2 participant plane is consistent with zero as expected if v_3 is due to fluctuations of the initial eccentricity

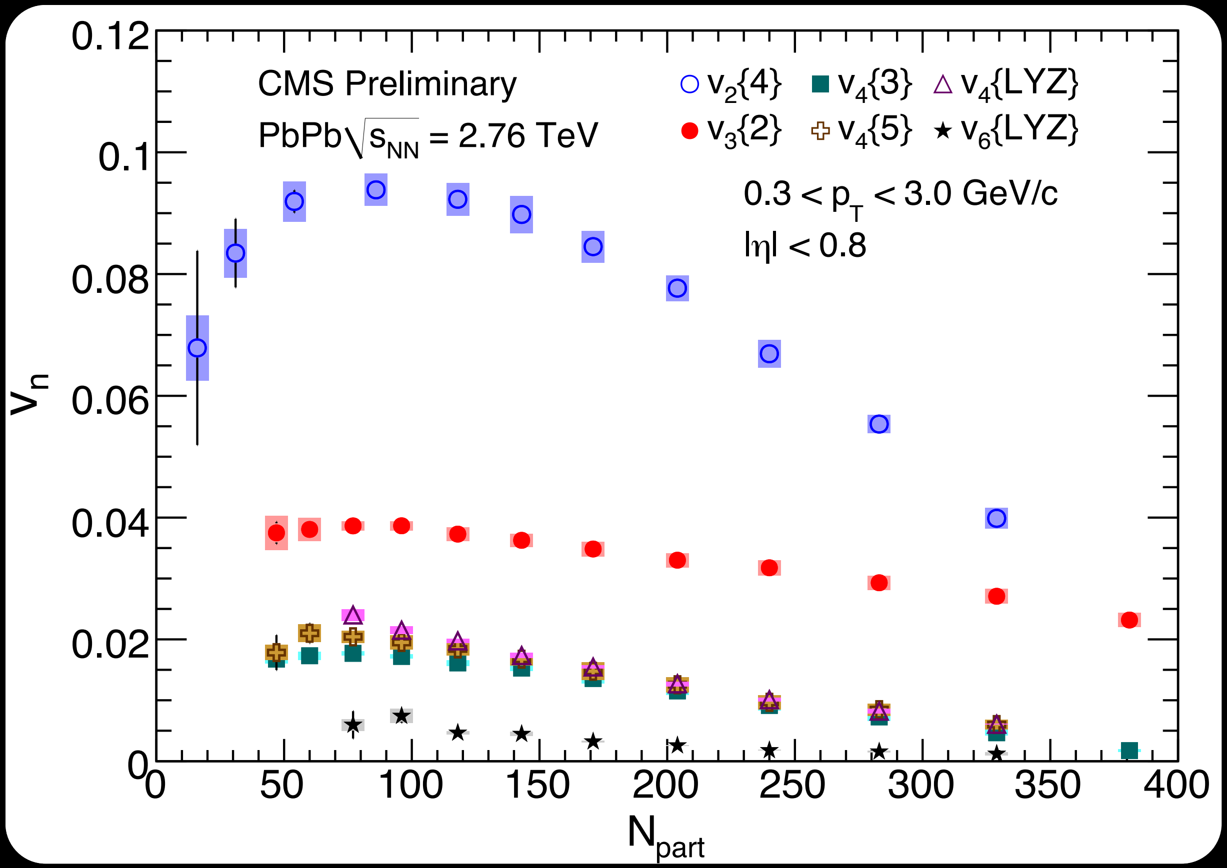
The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations



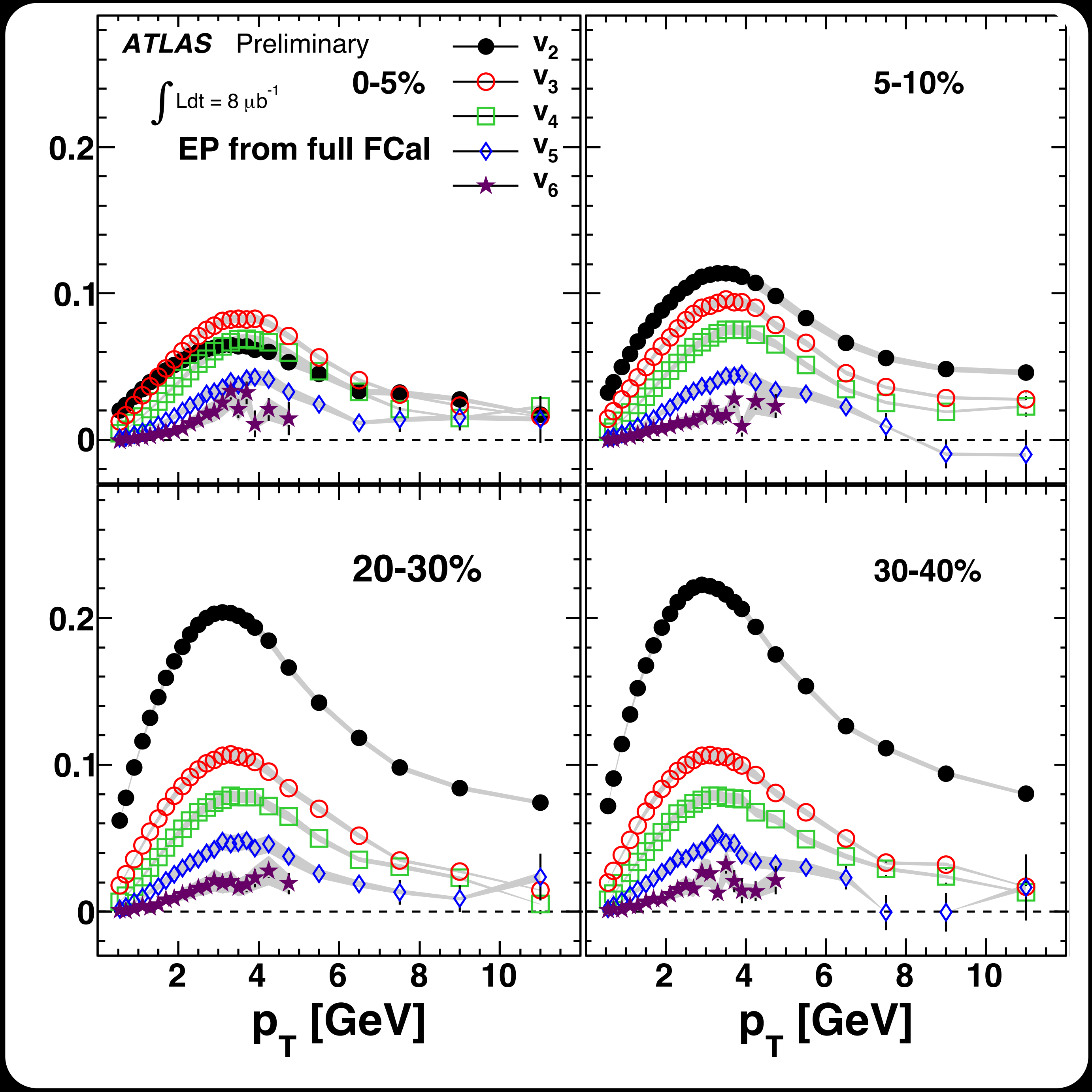
ALICE Collaboration, arXiv:1105.3865
PRL 107 (2011) 032301

We observe significant v_3 and v_4 which compared to v_2 has a different centrality dependence (already strong constrain for η/s)

the v_n's



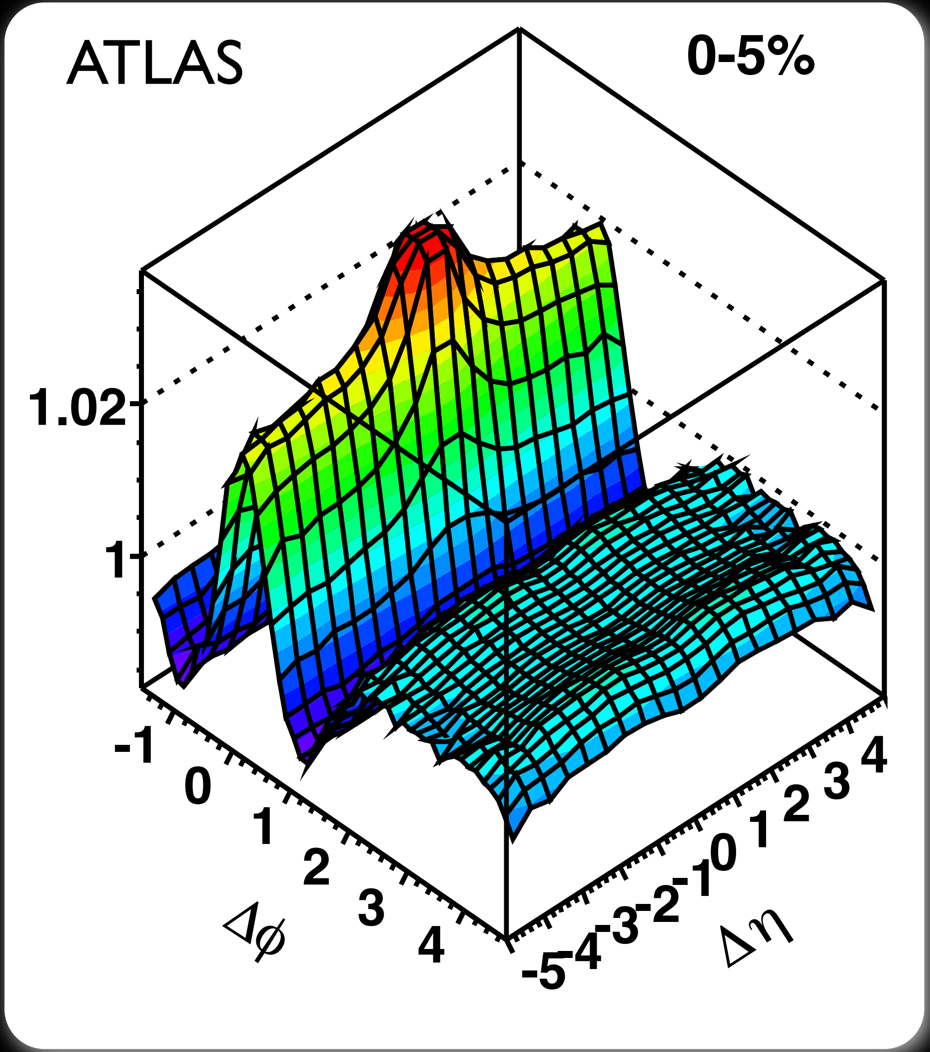
CMS PAS HIN-11-005

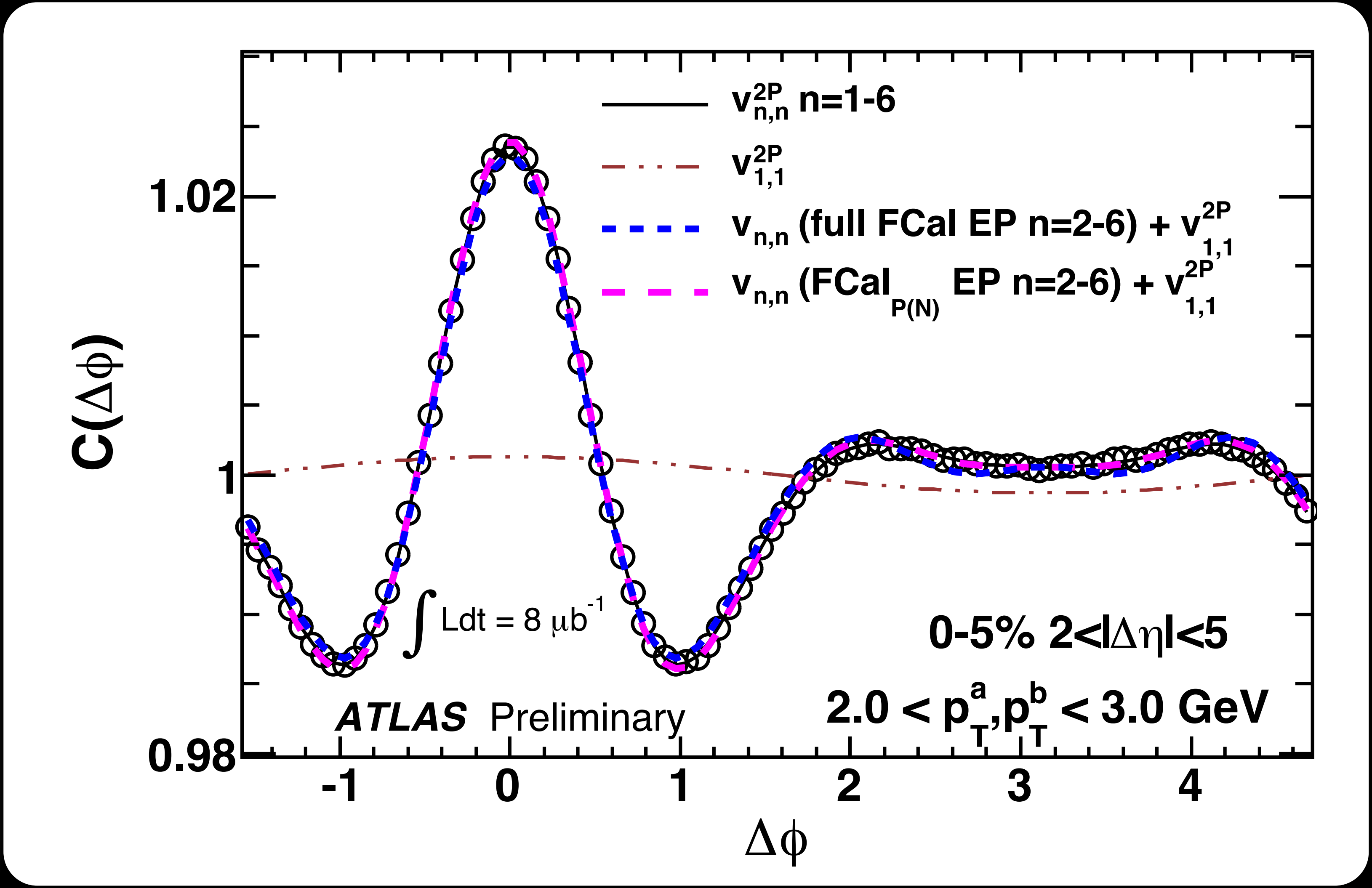


ATLAS-CONF-2011-074

For most central collisions v_3 and v_4 become at intermediate p_t larger than v_2

Angular Correlations





ATLAS-CONF-2011-074

Two particle azimuthal correlations can be described efficiently with the first 6 v_n coefficients and naturally explain the so called ridge and mach cone structure first observed at RHIC which were thought to be due to jet induced medium modifications

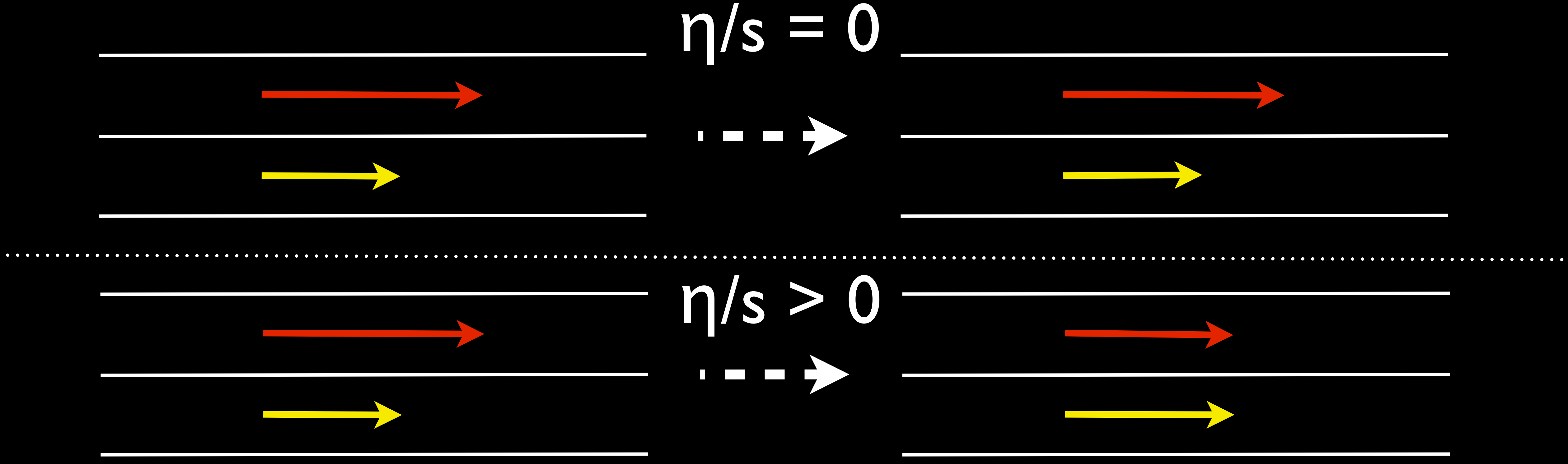
Conclusions

- Anisotropic flow measurements provide strong constraints on the bulk properties of hot and dense matter produced at RHIC and LHC energies and have led to the new paradigm of the QGP as the so called perfect liquid
  - At the LHC we observe even stronger flow than at RHIC which is expected for almost perfect fluid behavior
- The first measurements of v_3 and higher v_n's have recently been made at RHIC and at the LHC and indicate that these flow coefficients behave as expected from fluctuations of the initial spatial eccentricity (geometry!) and a created system which has a small η/s
  - provide new strong experimental constraints on η/s and initial conditions

Thanks

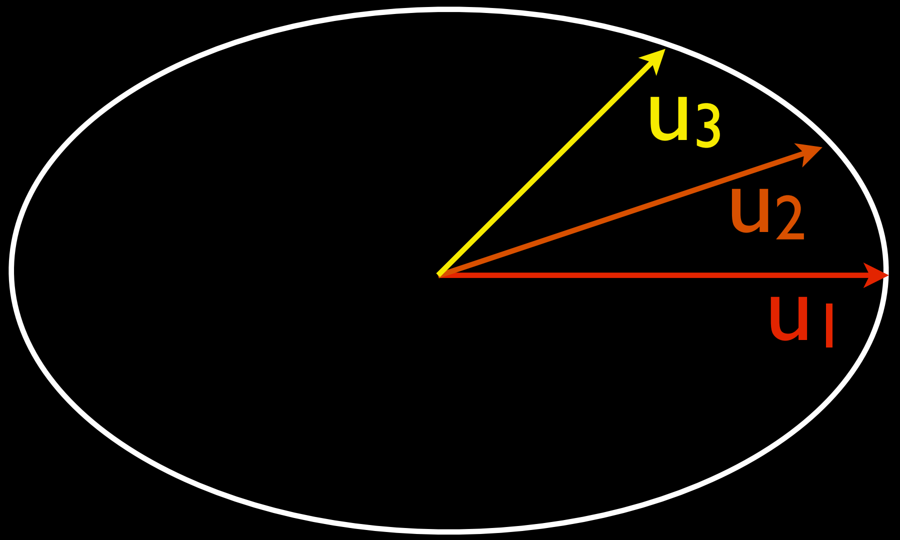
Backup

Shear Viscosity



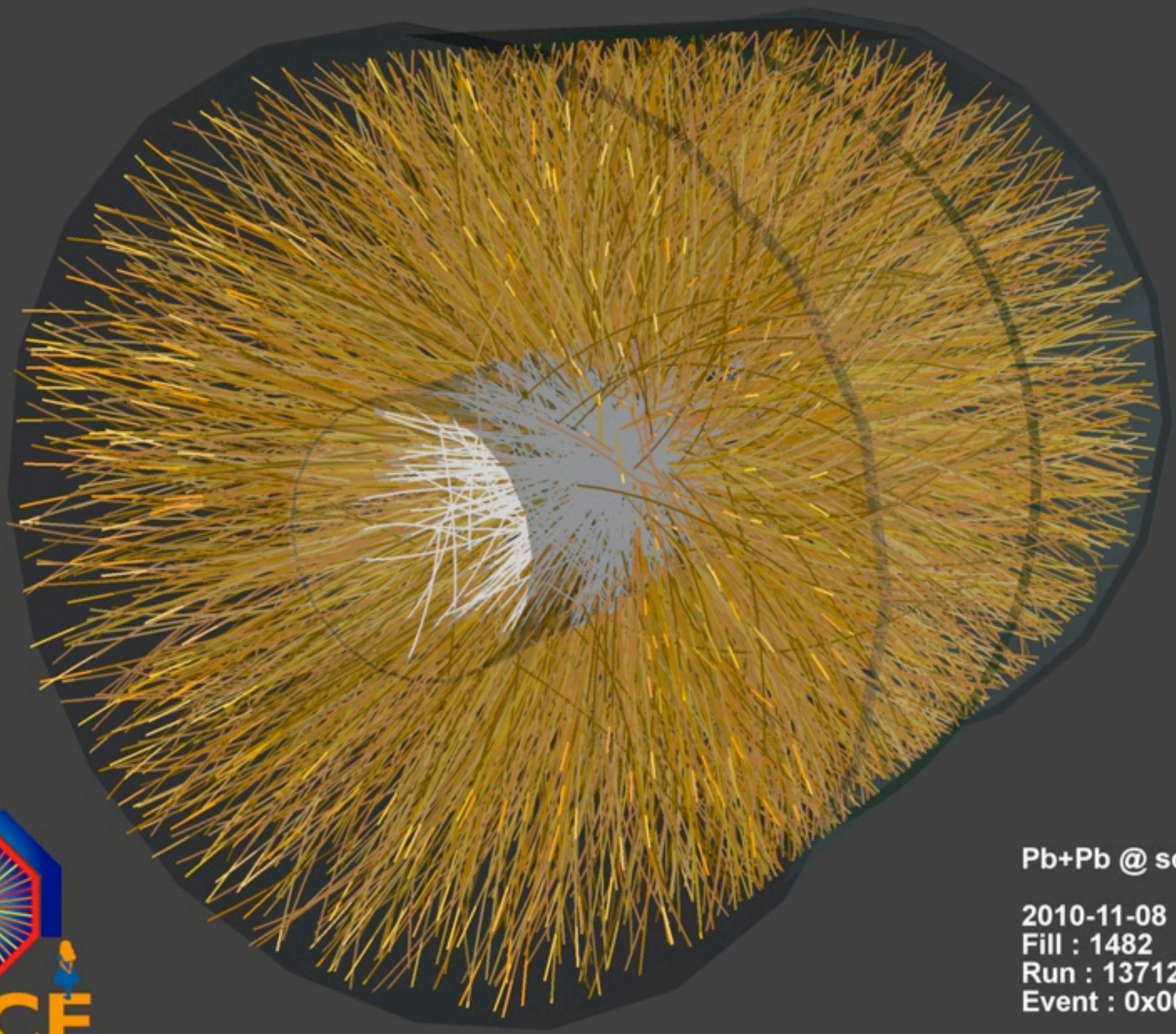
$\eta/s = 0$

$\eta/s > 0$



$u_1 > u_2 > u_3$ shear viscosity will make them equal and destroy the elliptic flow v_2 higher harmonics represent smaller differences which get destroyed more easily, and which, if measurable, makes them more sensitive probes to η/s

First Pb-Pb collisions!



ALICE

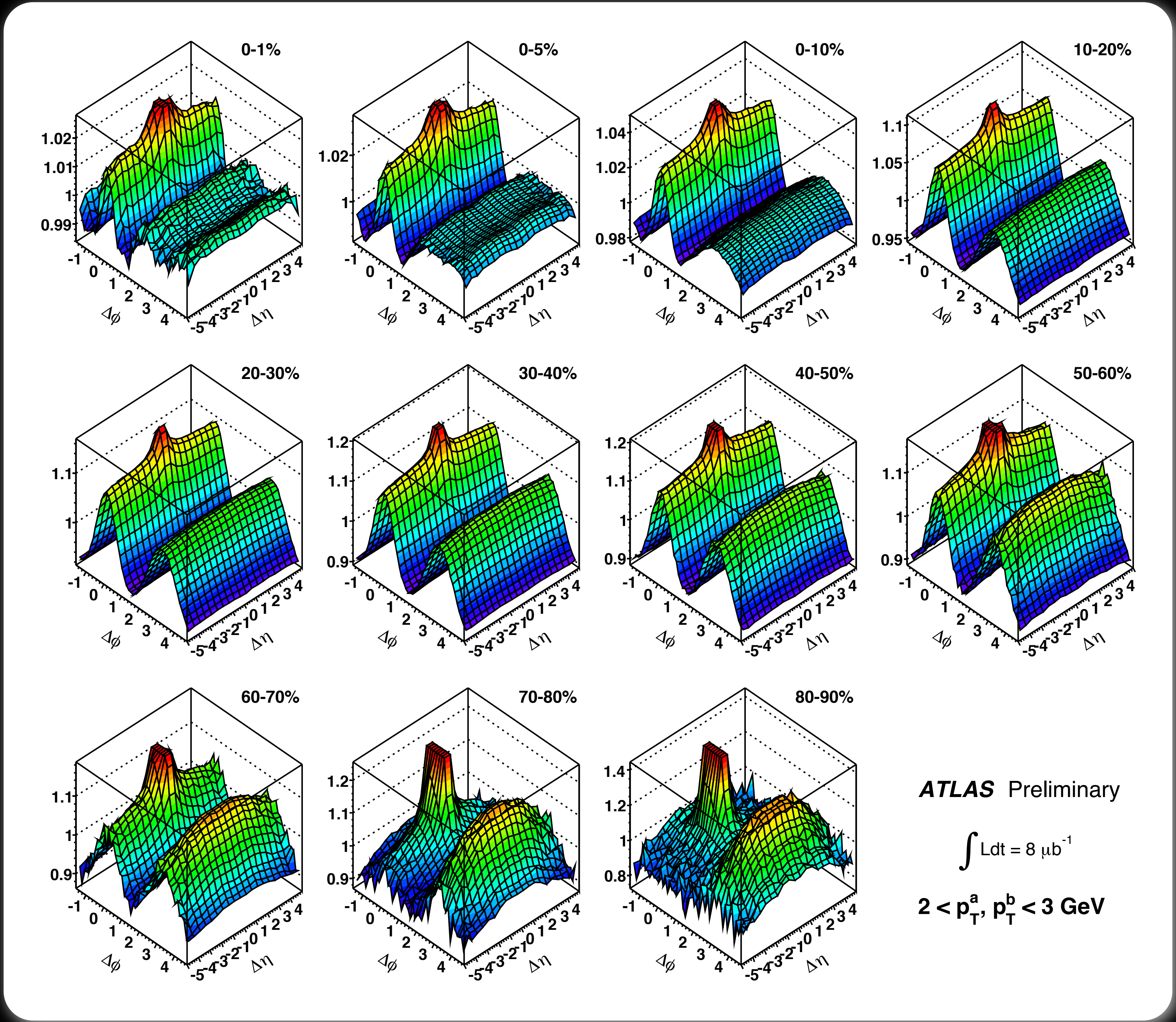
Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

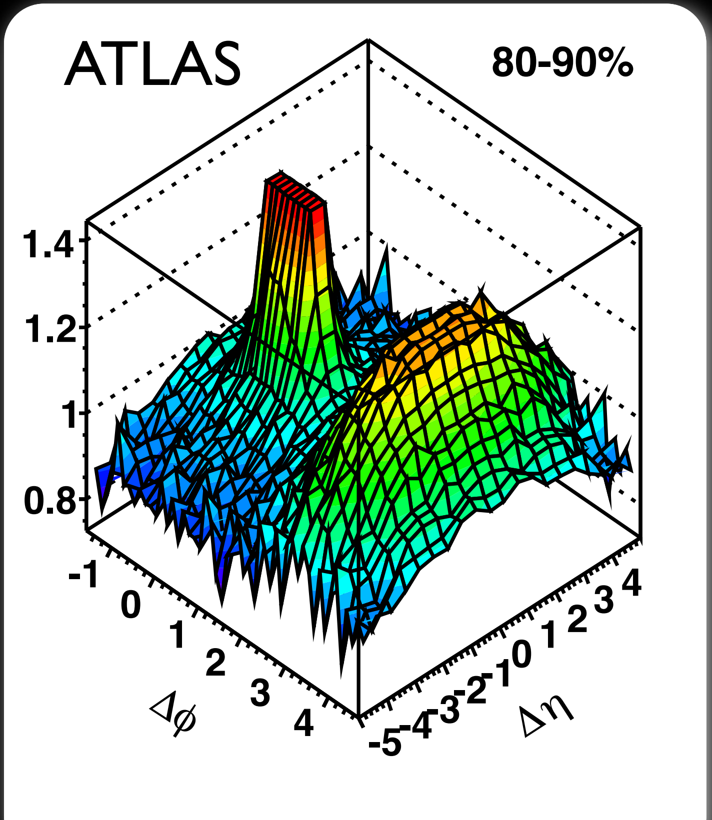
Angular Correlations at the LHC

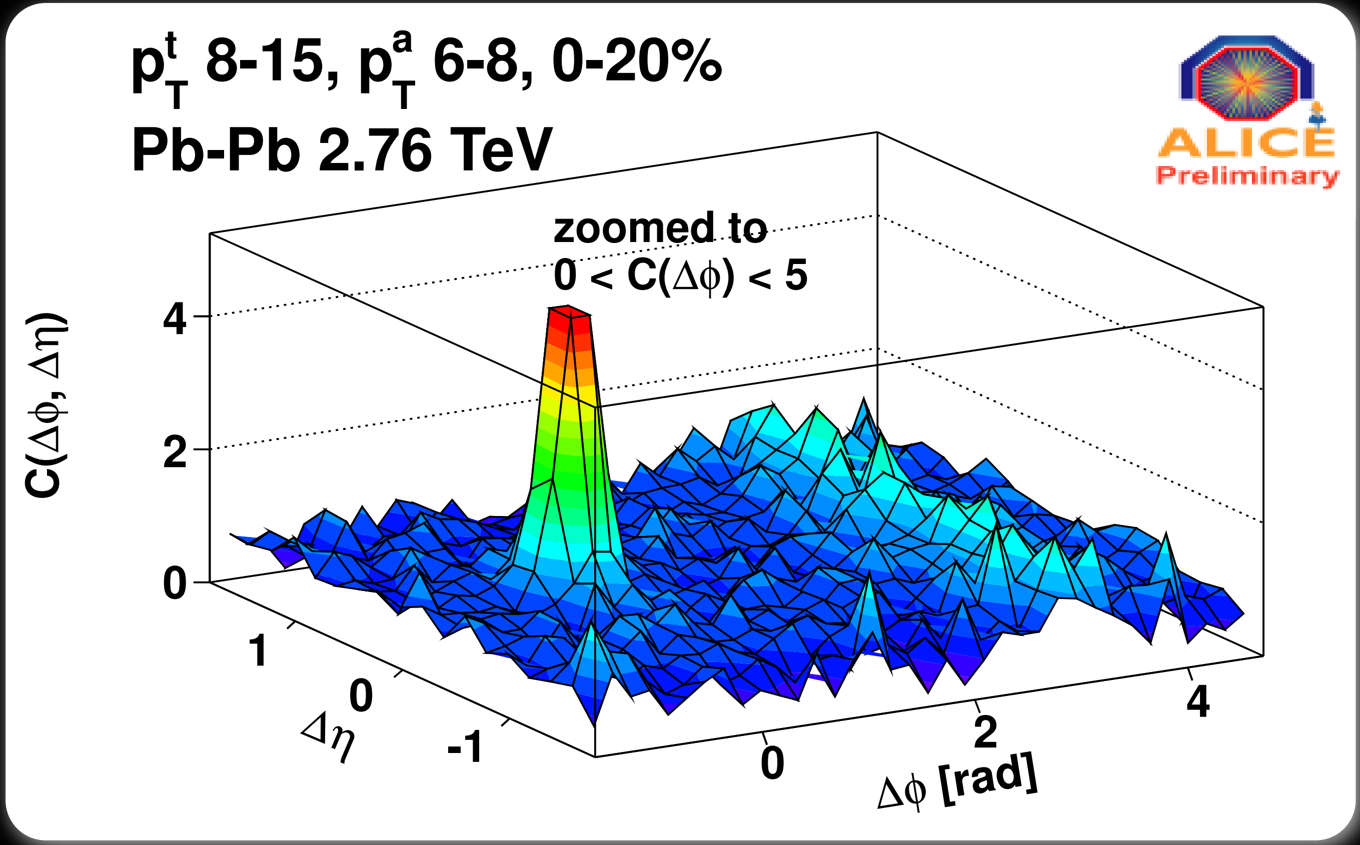
$$C(\Delta\phi\Delta\eta) \equiv \frac{N_{\mathrm{mixed}}}{N_{\mathrm{same}}} \frac{\mathrm{d}^2 N_{\mathrm{same}}/\mathrm{d}\Delta\phi \mathrm{d}\Delta\eta}{\mathrm{d}^2 N_{\mathrm{mixed}}/\mathrm{d}\Delta\phi \mathrm{d}\Delta\eta}$$

Contributions to the two-particle ΔΦ , Δη angular correlation come from anisotropic flow; v1, v2, v3, ..., Jets, resonances, HBT, etc



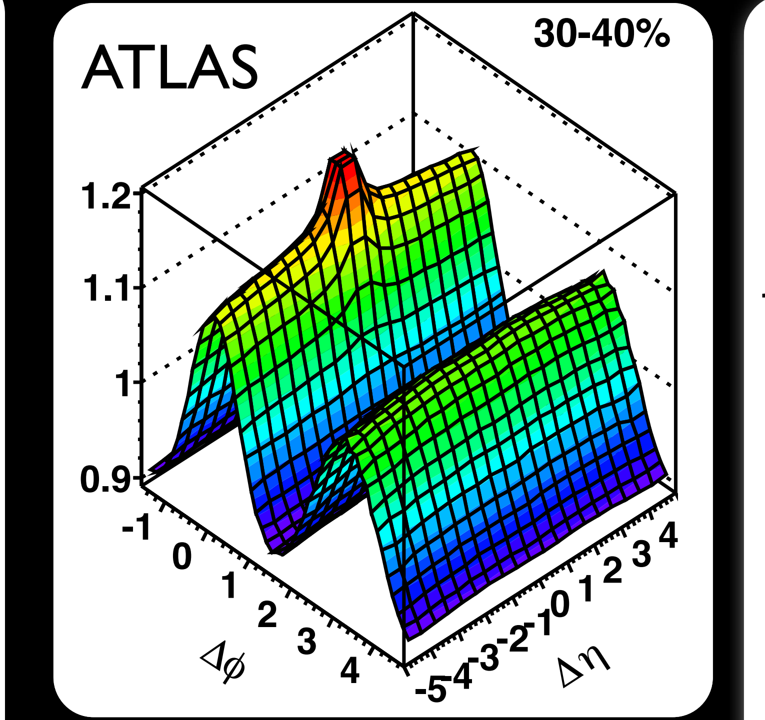
Angular Correlations

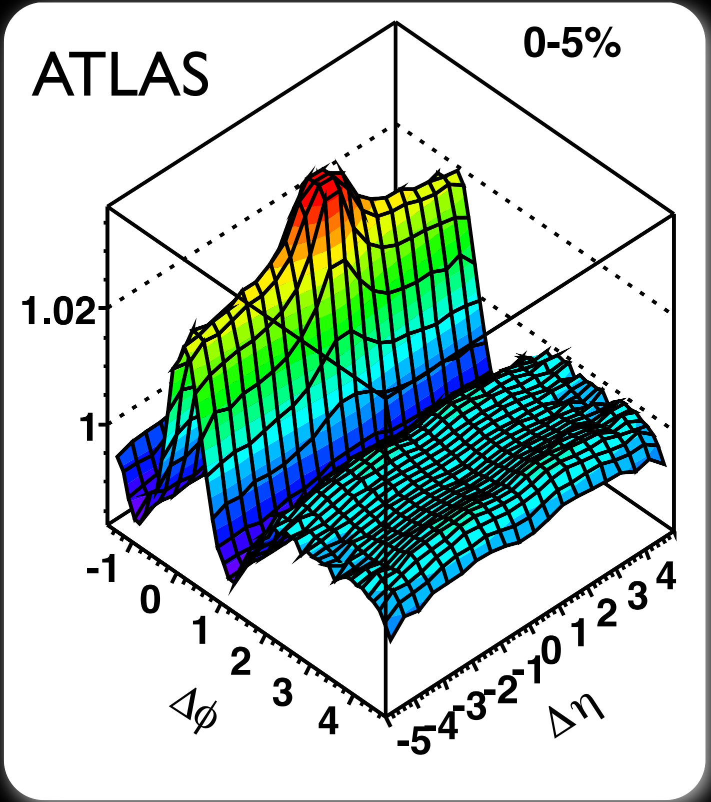




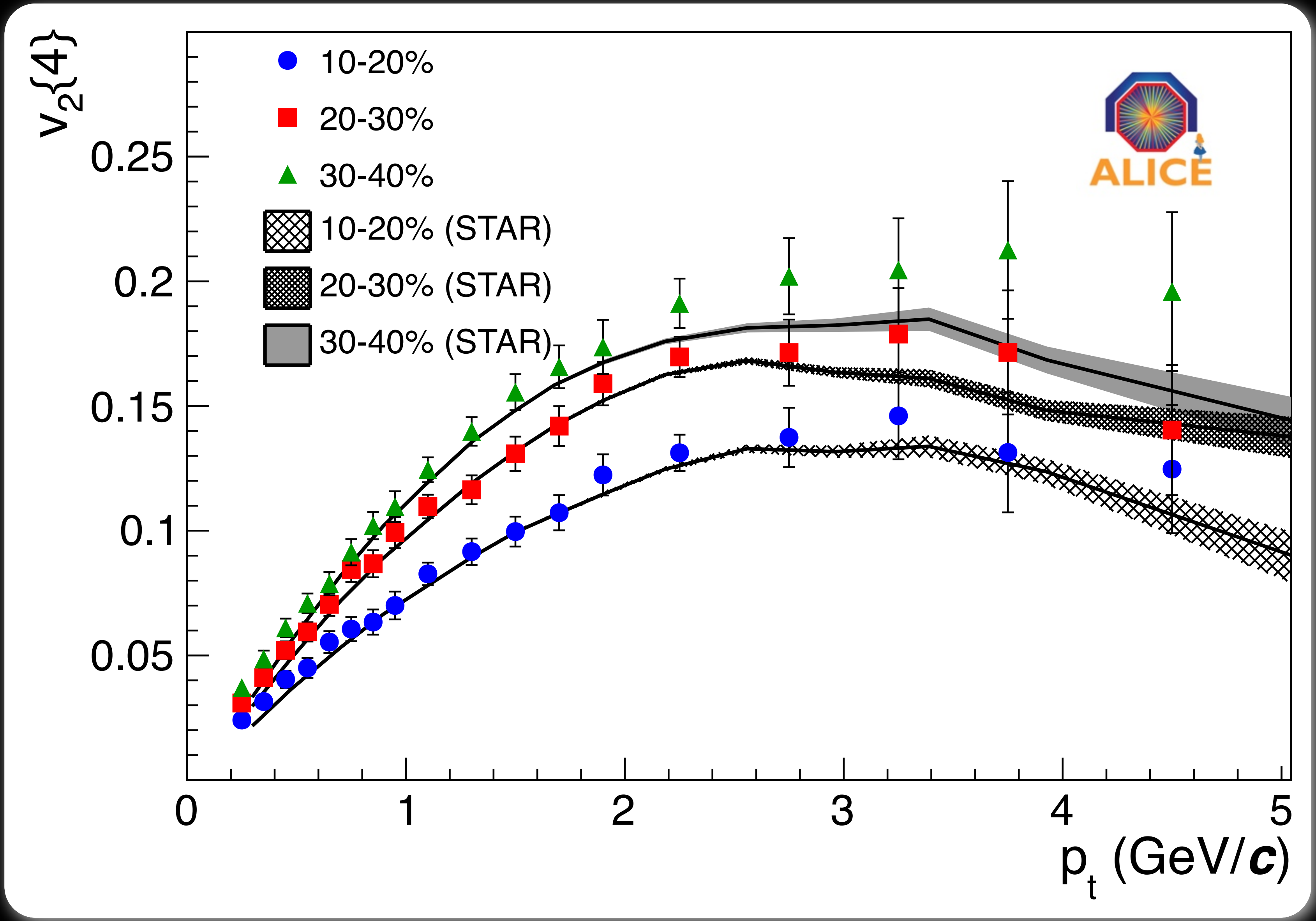
For very peripheral collisions or when triggered with a high-p_t charged particle the dominant contribution to two particle angular correlations is due to jet-correlations

More central heavy ion collisions look very very different!





v_2 as function of p_t

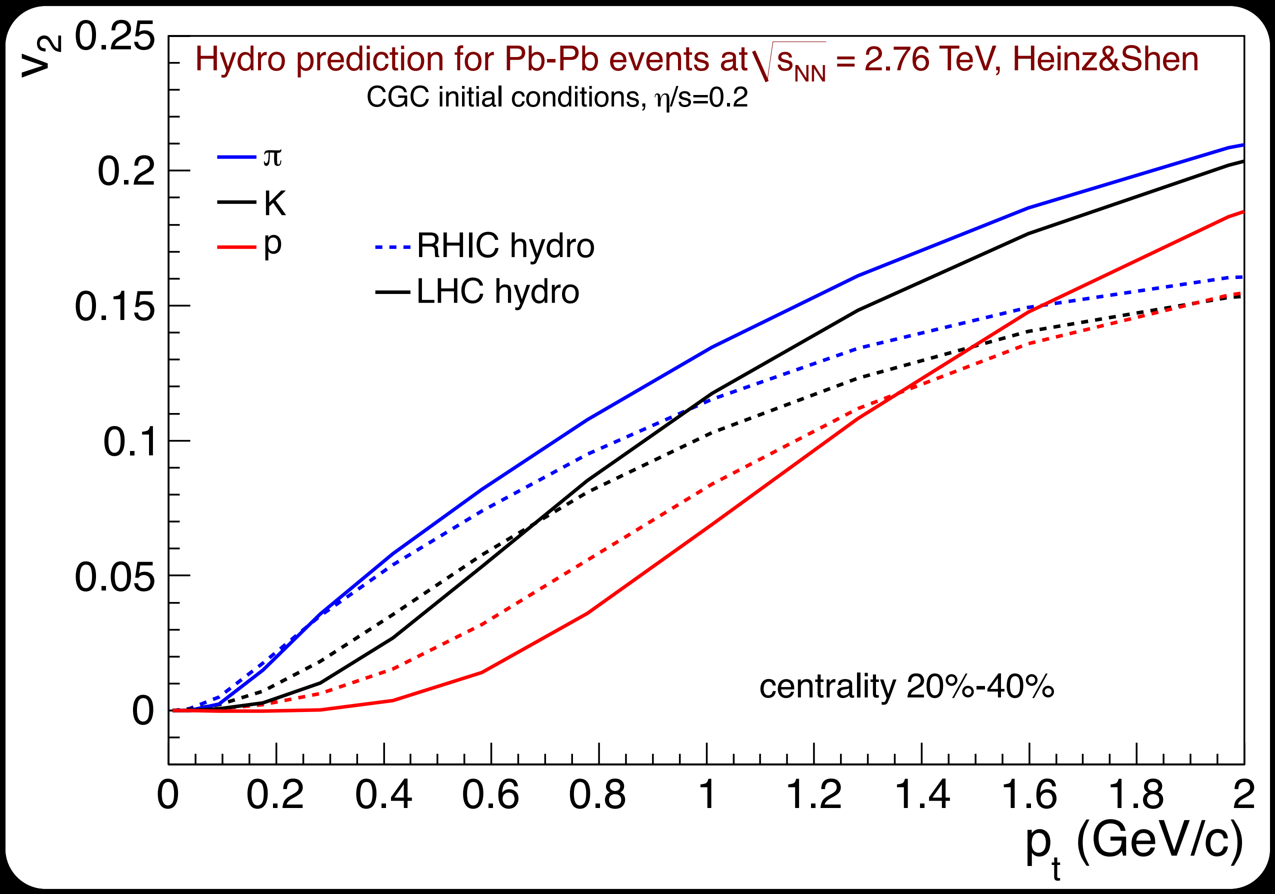


K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)

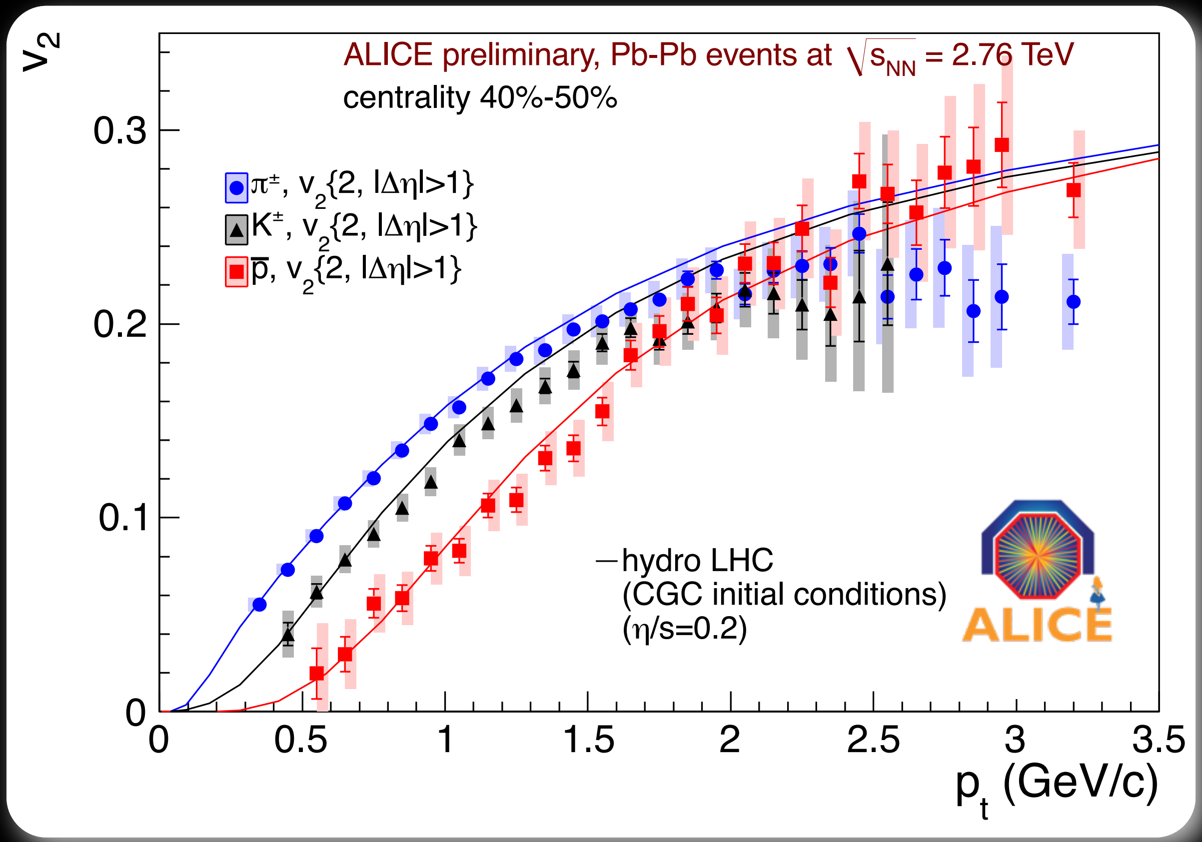
Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?

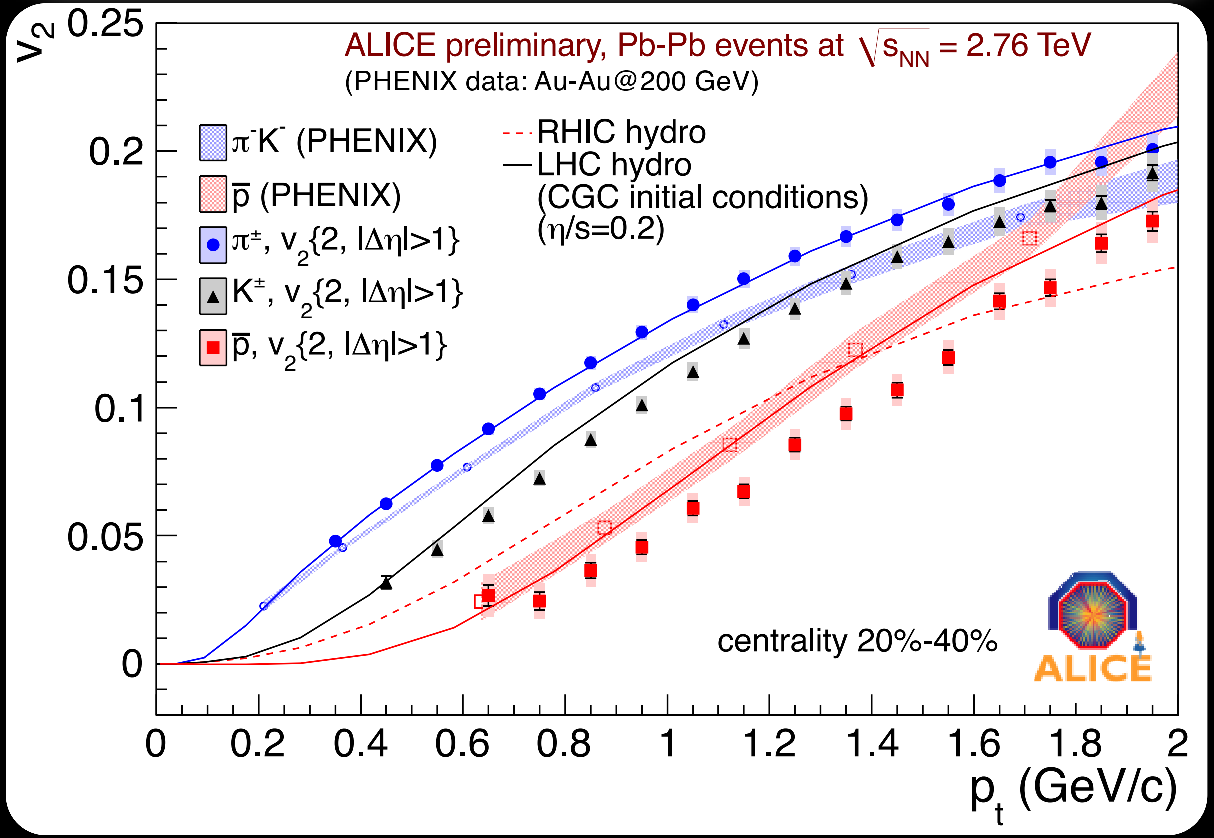
v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226



Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226



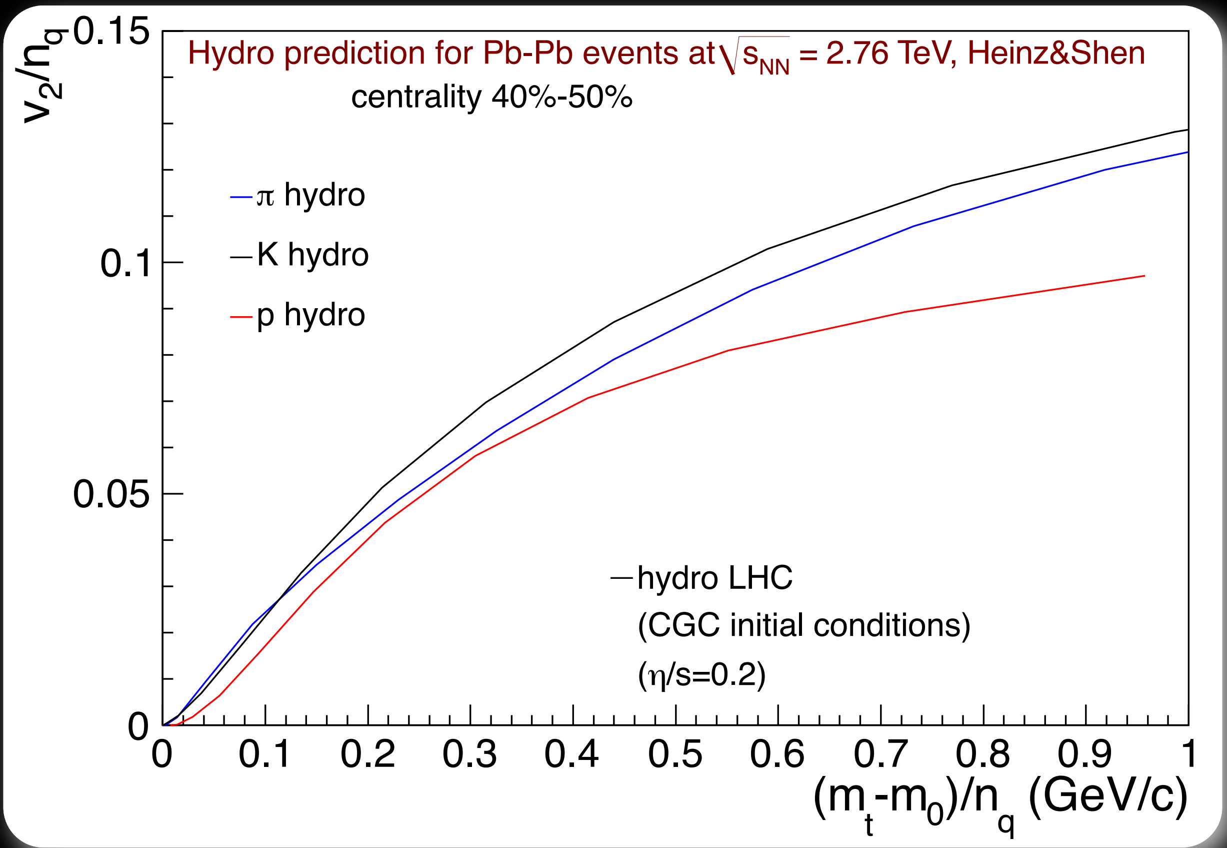


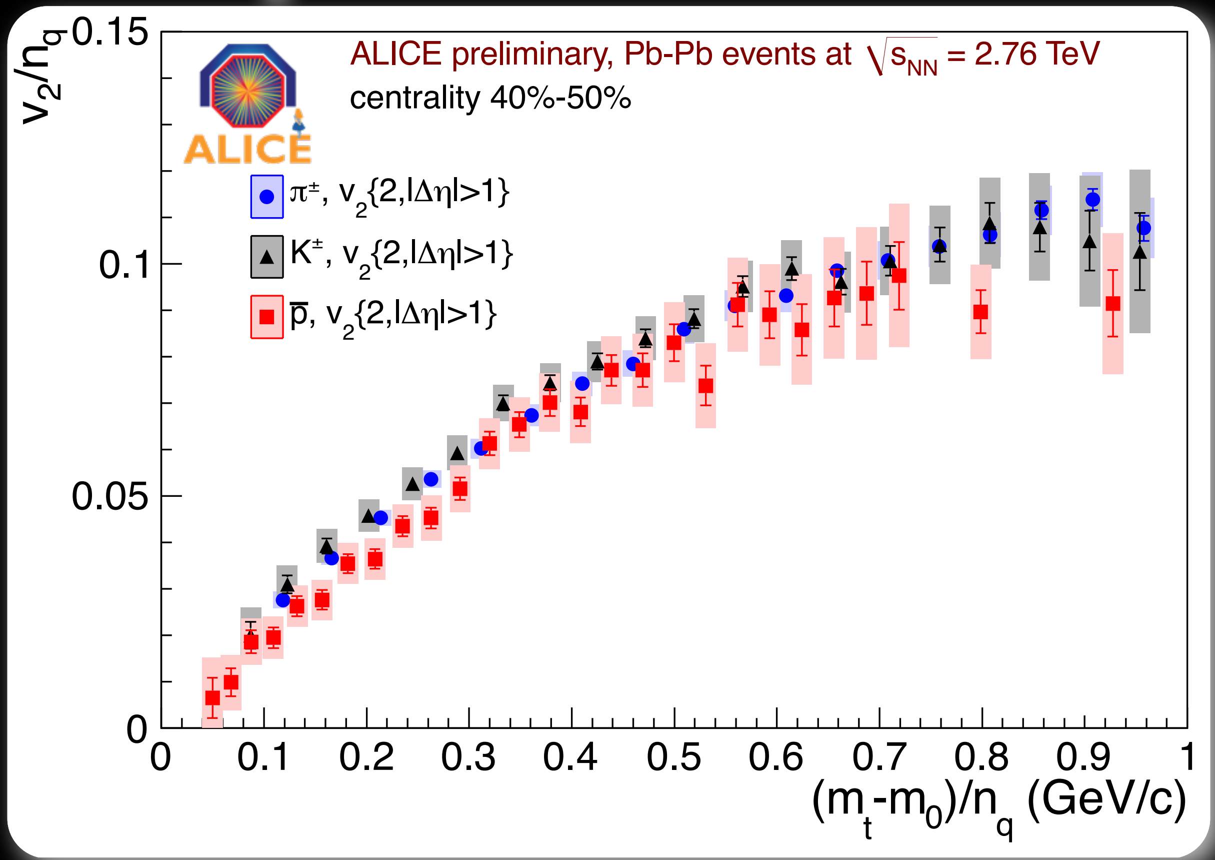
hydro models predict larger mass splitting

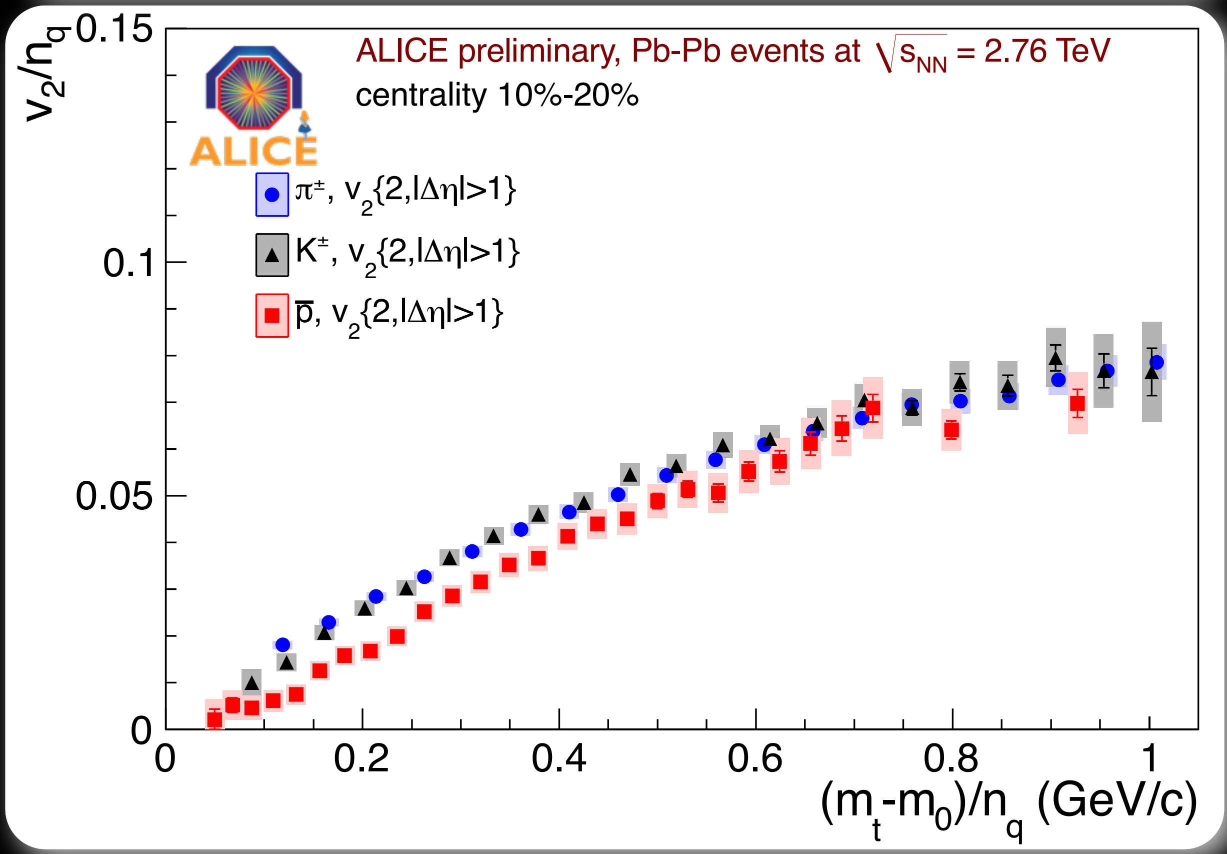
data shows mass splitting and agrees well with hydro predictions for mid-central collisions

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226







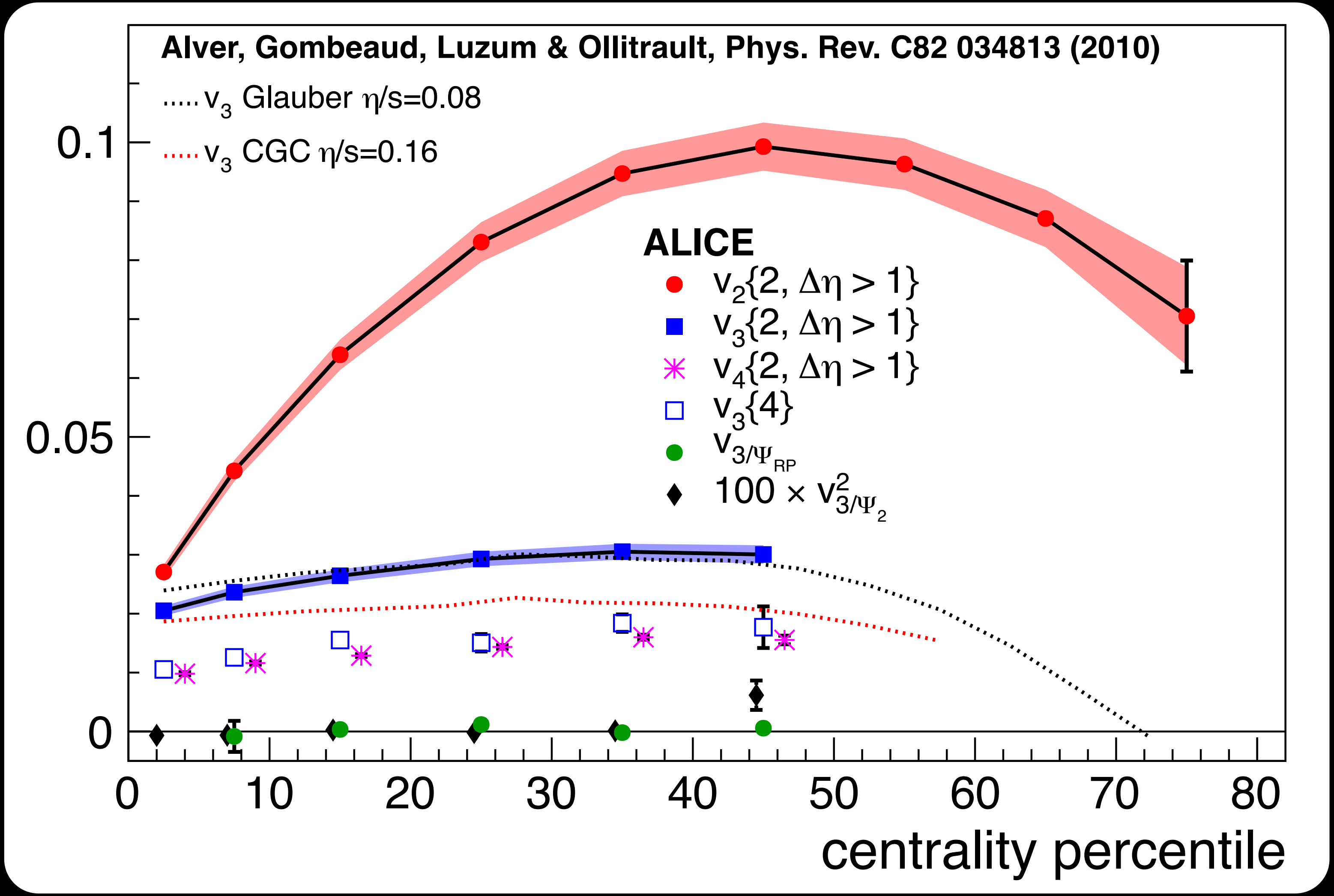
at small $(m_t-m_0)/n_q$ the scaling in the data resemble the scaling as observed in hydrodynamics

at large $(m_t-m_0)/n_q$ the quark scaling seems to work better

v_2, v_3 and v_4 at the LHC

We observe significant v_3 which compared to v_2 has a much weaker centrality dependence

The centrality dependence and magnitude are similar to predictions for MC Glauber with η/s=0.08 but above MC-KLN CGC with η/s=0.16

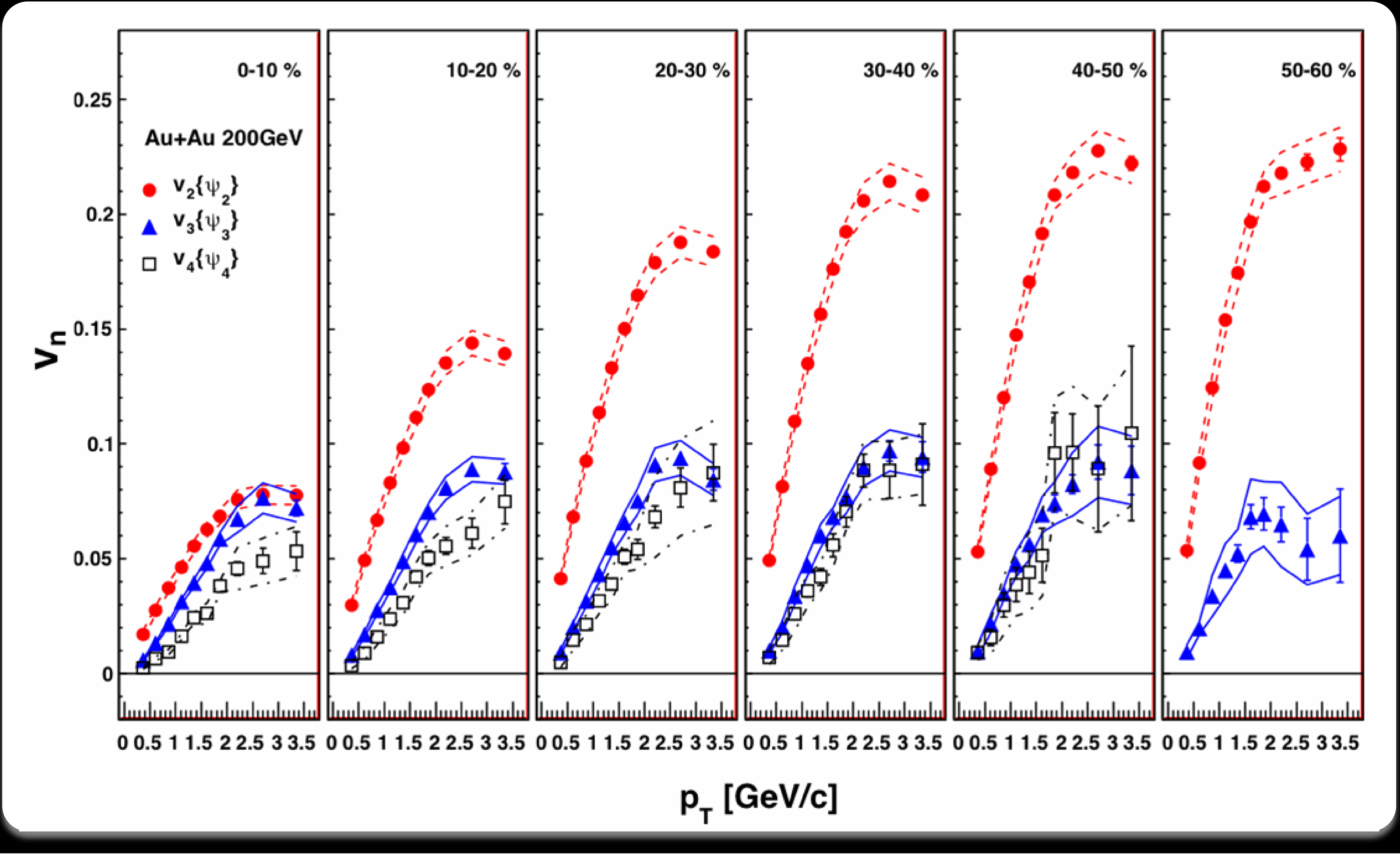


ALICE Collaboration, arXiv:1105.3865, PRL 107, 032301 (2011)

The v_3 with respect to the reaction plane determined in the ZDC and with the v_2 participant plane is consistent with zero as expected if v_3 is due to fluctuations of the initial eccentricity

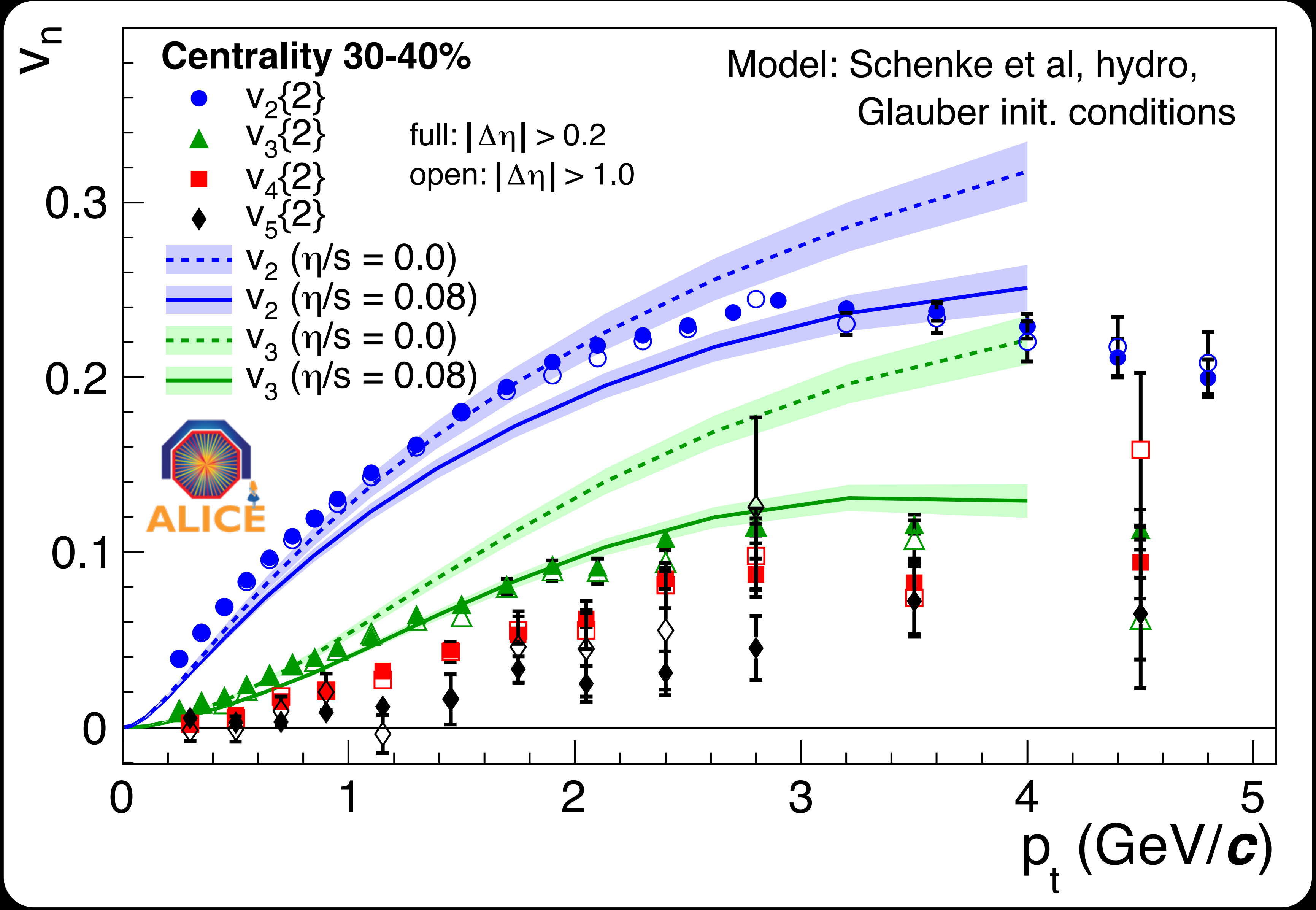
v_2, v_3 and v_4 at RHIC

PHENIX, arXiv:1105.3928



As at the LHC we observe at RHIC a significant v_3 and v_4 which compared to v_2 have a much weaker centrality dependence

v_2, v_3, v_4 and v_5 at the LHC

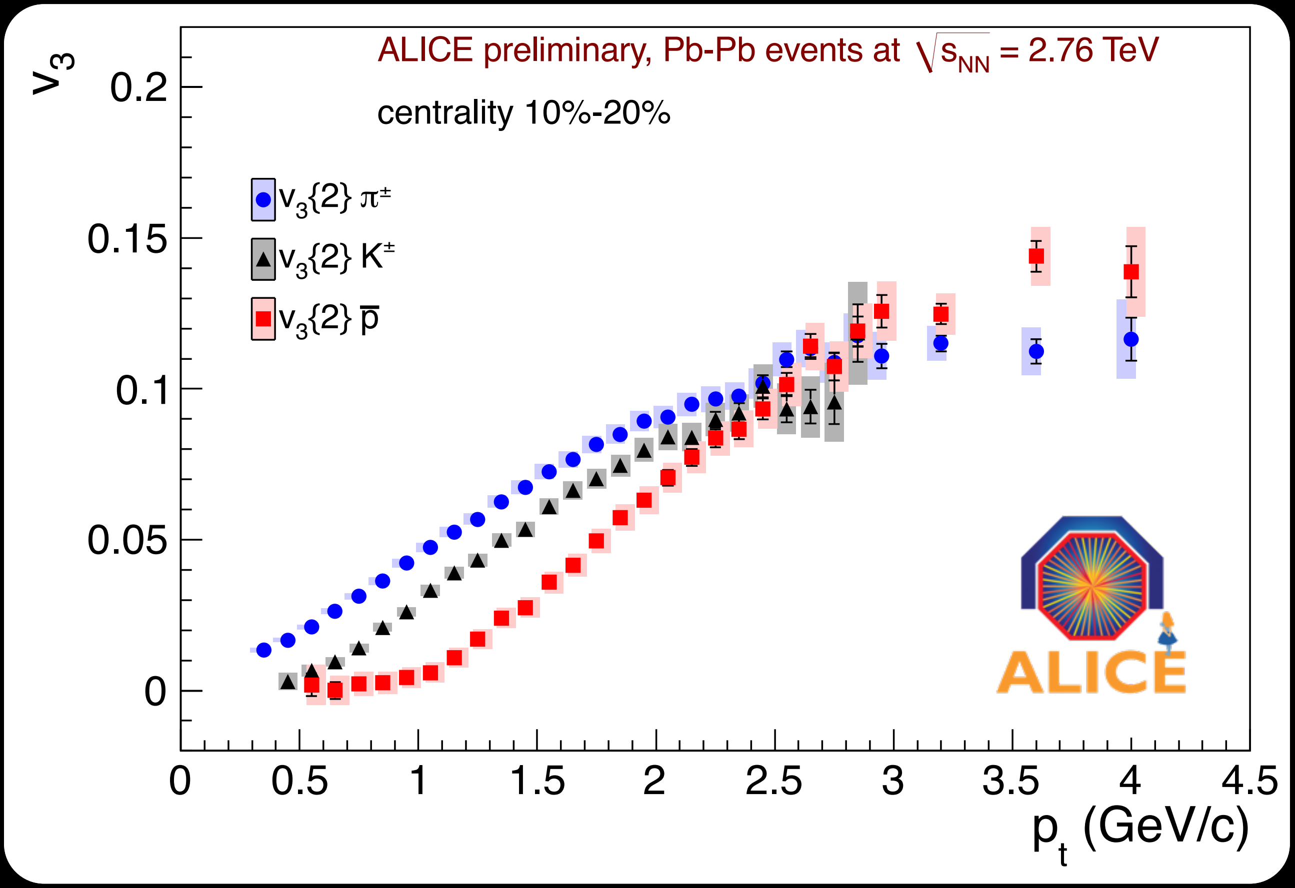


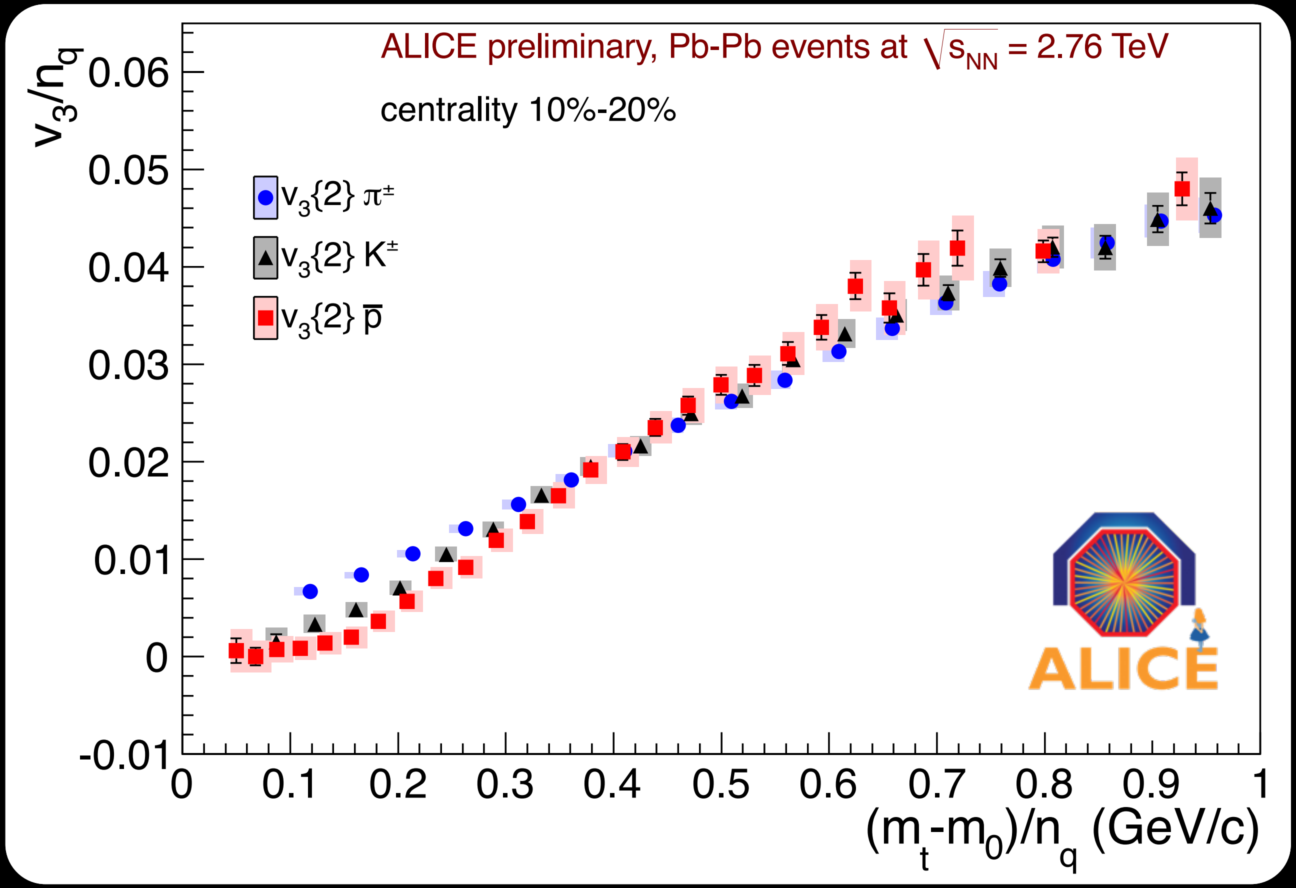
ALICE Collaboration, arXiv:1105.3865, PRL 107, 032301 (2011)

The overall dependence of v_2 and v_3 is described

However there is no simultaneous description with a single η/s of v_2 and v_3 for Glauber initial conditions

Triangular Flow

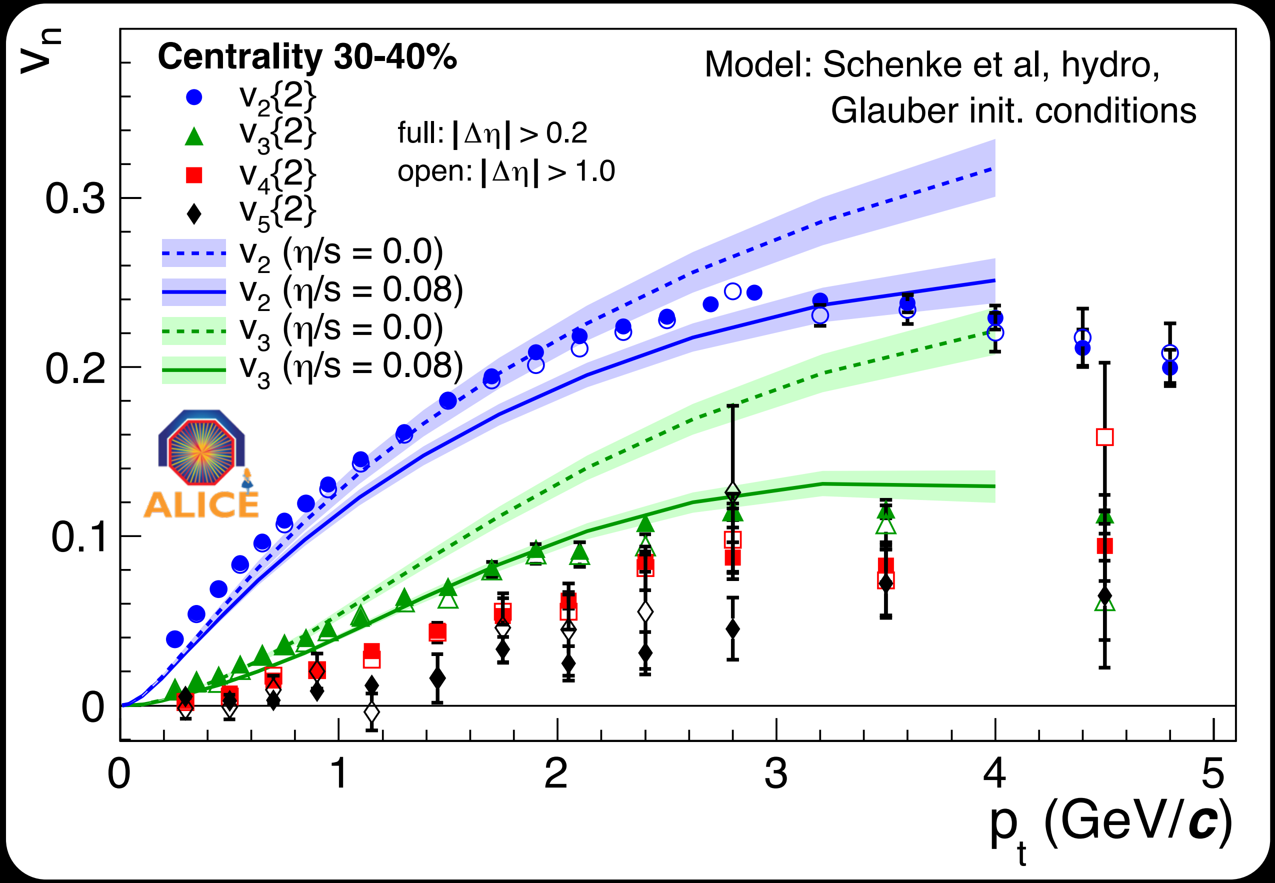


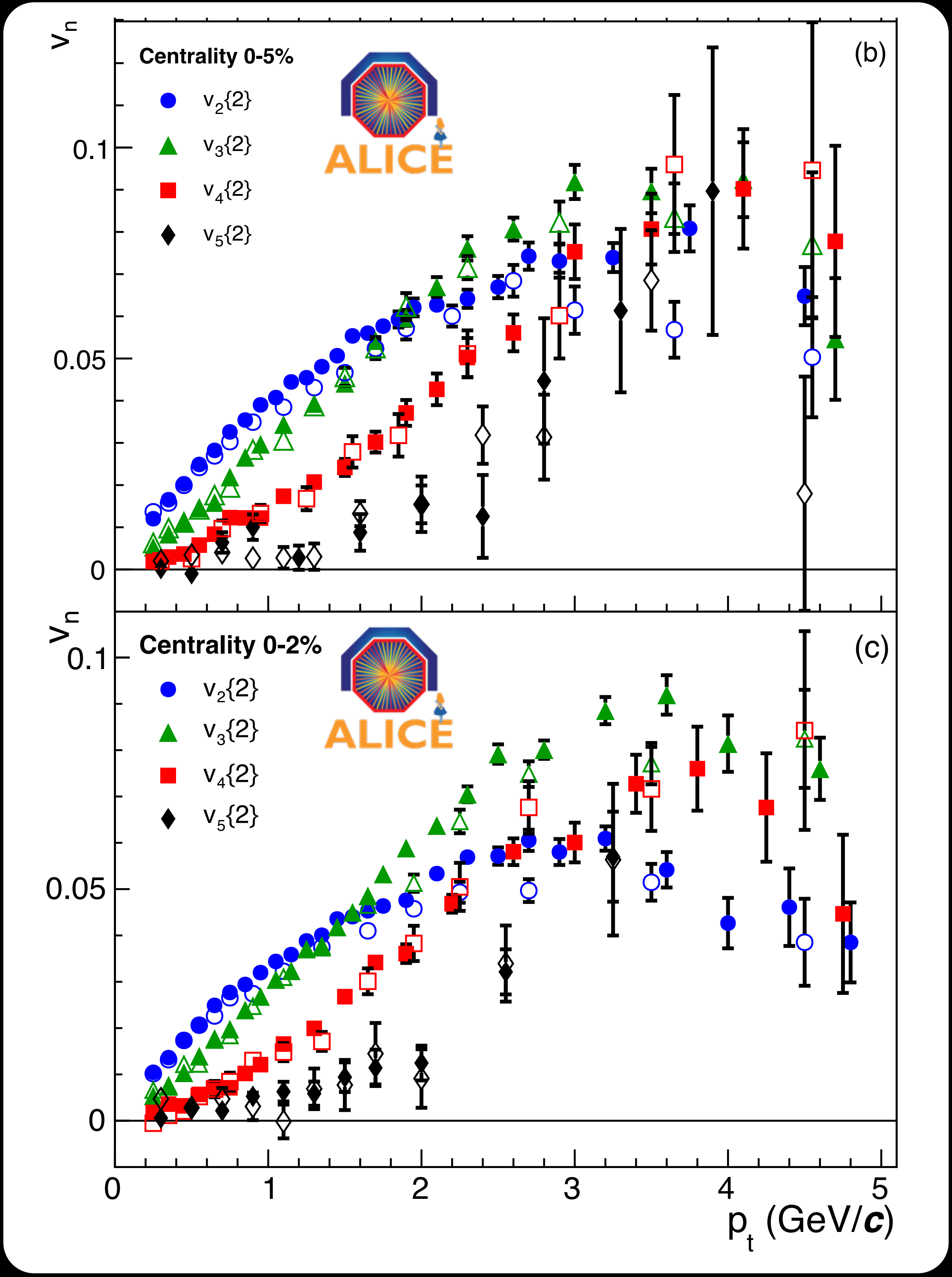


The behavior of v_3 as function of p_t for pions, Kaons and protons shows the same features as we already observed for v_2

(we observe the mass splitting and, in addition, the crossing of the pions with protons at intermediate p_t, which for v_2 was considered as a signature for coalescence/recombination)

Other Harmonics



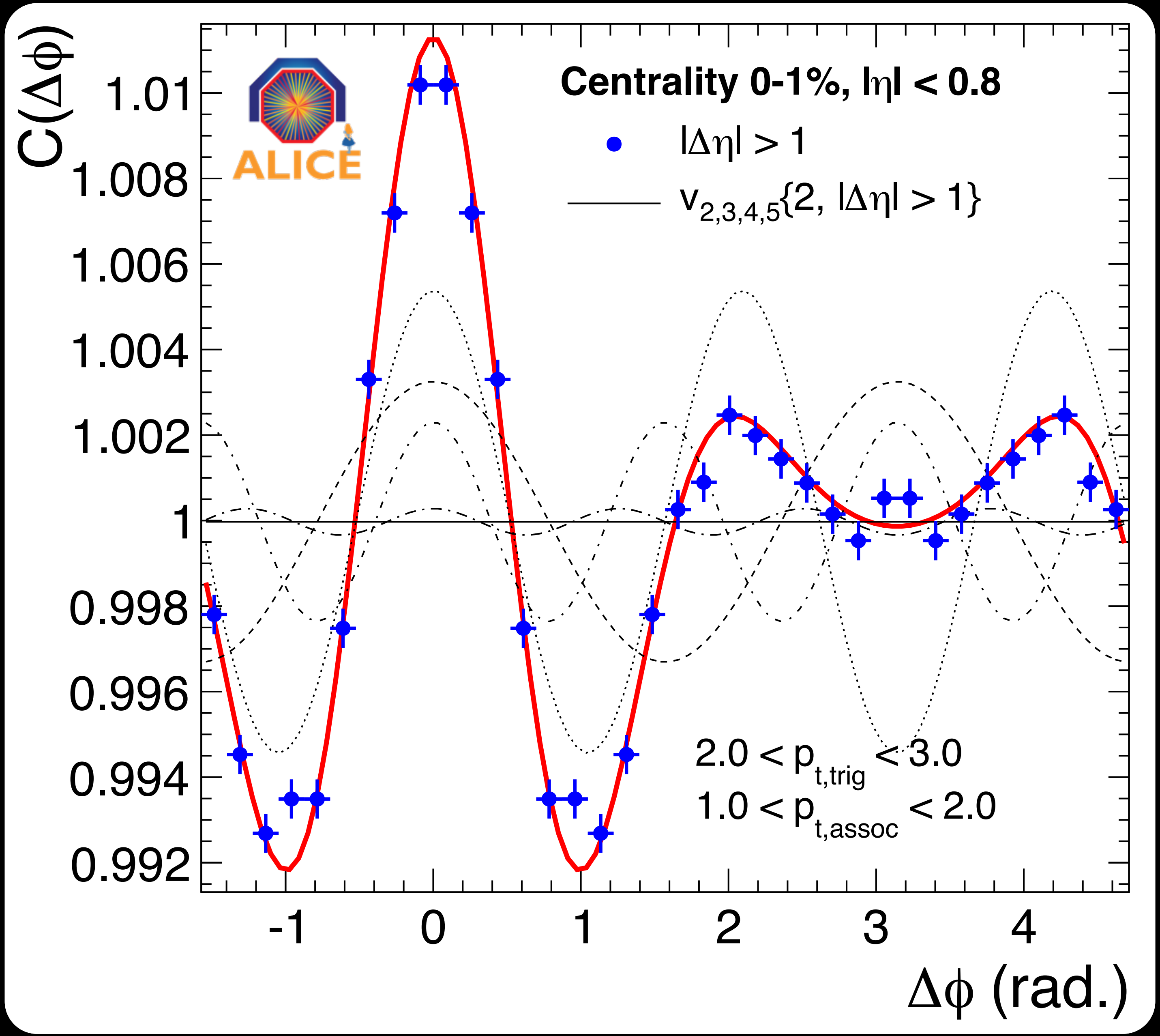


ALICE Collaboration, arXiv:1105.3865, PRL 107, 032301 (2011)

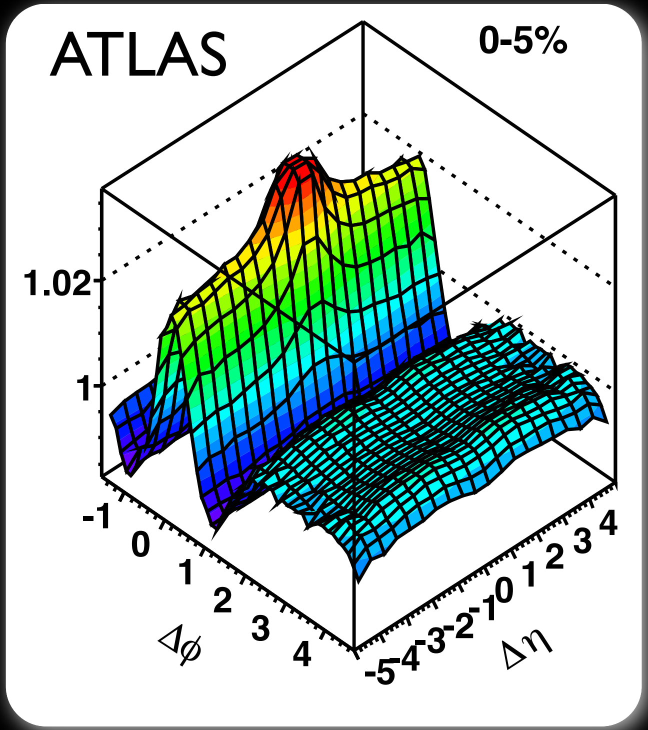
For central collisions at intermediate p_t the higher harmonics v_3 and v_4 cross v_2 and become the dominant harmonics

For more central collisions this occurs already at lower p_t

Other Harmonics



ALICE Collaboration, arXiv:1105.3865



We observe a doubly-peaked structure in the azimuthal correlation function opposite to the trigger particle

The red line shows the sum of the measured anisotropic flow Fourier coefficients. Those flow coefficients give a natural description of the observed correlation structure (no need for Mach cones)

$$C(\Delta\phi) \equiv \frac{N_{\rm mixed}}{N_{\rm same}} \frac{{\rm d}N_{\rm same}/{\rm d}\Delta\phi}{{\rm d}N_{\rm mixed}/{\rm d}\Delta\phi}$$